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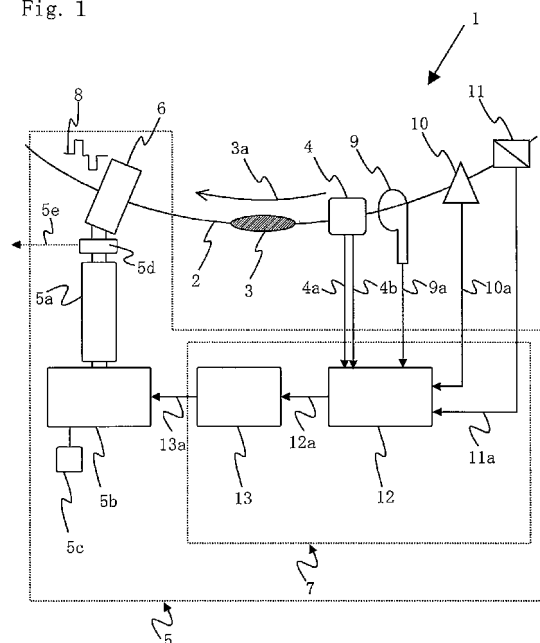
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(54) **INDUCTION ACCELERATOR AND METHOD OF ACCELERATING ELECTRICALLY-CHARGED PARTICLES**

(57) The present invention provides a set of induction accelerating cell for controlling acceleration of a charged particle beam and an induction accelerating device for controlling generation timing of an induced voltage applied by the induction accelerating cell in a synchrotron. The induction accelerating device in a synchrotron includes: an induction accelerating cell that applies an induced voltage; a switching power supply that supplies a pulse voltage to the induction accelerating cell via a transmission line and drives said induction accelerating cell; a DC power supply that supplies electric power to the switching power supply; and an intelligent control device including a pattern generator that generates a gate signal pattern for controlling on/off the switching power supply, and a digital signal processing device that controls on/off a gate master signal that becomes the basis of the gate signal pattern.

Fig. 1



Description

Technical Field

5 **[0001]** The present invention relates to an induction accelerating device that controls generation timing of an induced voltage applied from an induction accelerating cell and allows acceleration of a charged particle beam in a synchrotron using the induction accelerating cell, and an acceleration method of a charged particle beam.

Background Art

10 **[0002]** Charged particles collectively refer to "particles with charges" such as ions that are certain elements in the periodic table in a certain positive or negative charge state, and electrons. Further, the charged particles include particles consisting of a large number of molecules such as compounds or protein.

15 **[0003]** Synchrotrons include rf synchrotrons and synchrotrons using an induction accelerating cell. An rf synchrotron is a circular accelerator for applying, with an rf acceleration cavity, an rf acceleration voltage synchronized with a magnetic field excitation pattern of a bending magnet that ensures strong focusing of a design orbit along which a charged particle beam circulates to charged particles such as protons injected into a vacuum duct by an injector, and circulating the charged particles along the design orbit in the vacuum duct.

20 **[0004]** In the rf synchrotron, the injected charged particles in the form of several bunches circulate along the design orbit of the rf synchrotron. When a bunch arrives at the rf acceleration cavity, the bunch receives the rf acceleration voltage synchronized with the magnetic field excitation pattern to be accelerated up to a predetermined energy level.

[0005] The bunch refers to a group of charged particles that circulate along the design orbit with phase stability.

25 **[0006]** A voltage required for acceleration calculated from an inclination (the time rate of change) of the magnetic field excitation pattern of the bending magnet is applied to the bunch as an rf acceleration voltage. The rf acceleration voltage has both the function of supplying the voltage required for accelerating the bunch, and the function of confinement for preventing diffusion of the bunch in an advancing axis direction.

30 **[0007]** These two functions are essential for accelerating the bunch in the rf synchrotron. The function of confinement is sometimes particularly referred to as phase stability. The phase stability refers to a state in which, by the rf acceleration voltage, individual charged particles receive focusing forces in the advancing axis direction and are formed into a bunch, and circulate in the rf synchrotron while moving forward and backward in the advancing axis direction of the charged particles in the bunch. Time periods are limited in which the rf acceleration voltage has the two functions.

35 **[0008]** On the other hand, a synchrotron using an induction accelerating cell has a different acceleration principle from the rf synchrotron, and is a circular accelerator for applying an induced voltage to a charged particle beam with the induction accelerating cell for acceleration. Figure 16 shows an acceleration principle of charged particles by an induction accelerating cell.

40 **[0009]** Figure 16 shows the acceleration principle of a charged particle beam by induced voltages applied from conventional induction accelerating cells having different functions. The induction accelerating cells are classified according to their functions into an induction accelerating cell for confinement of charged particle beams in the advancing axis direction (hereinafter referred to as an induction accelerating cell for confinement), and an induction accelerating cell for applying induced voltages for accelerating the charged particle beams in the advancing axis direction (hereinafter referred to as an induction accelerating cell for acceleration).

[0010] An rf acceleration cavity may be used for confinement of a bunch 3 in the advancing axis direction instead of the induction accelerating cell for confinement. Thus, conventional acceleration of the charged particle beams using the induced voltages requires the two functions of acceleration and confinement.

45 **[0011]** Figure 16(A) shows confinement of the bunch 3 by the induction accelerating cell for confinement. The induced voltages applied to the bunch 3 by the induction accelerating cell for confinement are barrier voltages 17.

50 **[0012]** Particularly, a barrier voltage 17 applied to a bunch head 3d in a direction opposite to the advancing axis direction of the bunch 3 is a negative barrier voltage 17a, and a voltage value thereof is a negative barrier voltage value 17c. A barrier voltage 17 applied to a bunch tail 3e in the same direction as the advancing axis direction of the bunch 3 is a positive barrier voltage 17b, and a voltage value thereof is a positive barrier voltage value 17d.

[0013] These barrier voltages 17 provide phase stability to the bunch 3 like the conventional radio frequency waves. The axis of abscissa t represents changes with time in the induction accelerating cell for acceleration, and the axis of ordinate v represents an applied barrier voltage value (an induced voltage value for acceleration in Figure 16(B)).

55 **[0014]** Figure 16(B) shows acceleration of the bunch 3 by the induction accelerating cell for acceleration. Induced voltages applied to the bunch 3 by the induction accelerating cell for acceleration are induced voltages for acceleration 18. Particularly, an induced voltage for acceleration 18 applied to the entire bunch 3 from the bunch head 3d to the bunch tail 3e and required for accelerating the bunch 3 in the advancing axis direction is an acceleration voltage 18a, and a voltage value thereof is an acceleration voltage value. A time period when the acceleration voltage 18a is applied

is a charging time period 18e.

[0015] An induced voltage for acceleration 18 having a different polarity from the acceleration voltage 18a in a time period when no bunch 3 exists in the induction accelerating cell for acceleration is a reset voltage 18b, and a voltage value thereof is a reset voltage value 18d. The reset voltage 18b avoids magnetic saturation of the induction accelerating cell for acceleration.

[0016] It is considered that the barrier voltages 17 and the induced voltages for acceleration 18 allow acceleration of protons, which has been demonstrated as disclosed in "Phys. Rev. Lett. Vol. 94, No. 144801-4 (2005)" as Non-Patent Document 1.

[0017] Further, as disclosed in the bulletin of the Physical Society of Japan Vol. 59, No. 9 (2004) p601-p610 as Non-Patent Document 2, it is considered that the use of the induction accelerating cell allows acceleration of a bunch 3 (super-bunch) of 1 μ sec corresponding to a time width of several to ten times the length of the beam accelerated by the conventional rf synchrotron.

[0018] Figure 17 shows synchrotron oscillation. In the confinement and acceleration methods of the charged particles in the advancing axis direction in the rf synchrotron, it is known that a phase space area in which the bunch 3 can be confined is restricted in principle particularly in the advancing axis direction (time axis direction).

[0019] Specifically, in a time area where the radio frequency waves 36 are at a negative voltage, the bunch 3 is reduced in speed, and in a time area with a different polarity of a voltage gradient, the charged particles diffuse in the advancing axis direction and are not confined. In other words, only an acceleration area 36a shown by the double-headed dotted arrow can be used for accelerating the bunch 3.

[0020] In the acceleration area 36a, the phase of the radio frequency waves 36 is moved and controlled to apply a center acceleration voltage 3f that is a constant voltage to a bunch center 3c. Thus, the charged particles positioned in the bunch head 3d have higher energy and arrive earlier at the rf acceleration cavity than the bunch center 3c does, and thus receive a lower head acceleration voltage 3g than the center acceleration voltage 3f received in the bunch center 3c and reduce their speed.

[0021] On the other hand, the charged particles positioned in the bunch tail 3e have lower energy and arrive later at the rf acceleration cavity than the bunch center 3c does, and thus receive a greater tail acceleration voltage 3h than the center acceleration voltage 3f received in the bunch center 3c and increase their speed. During the acceleration, the charged particles repeat this process.

[0022] This is phase stability, and the phase stability, resonance acceleration, and strong focusing are three main principles for allowing synchrotron acceleration of charged particles.

[0023] A state where the phase stability is provided to the bunch 3, and the charged particles that constitute the bunch 3 rotate forward and backward in an acceleration direction symmetrically with respect to the bunch center 3c is synchrotron oscillation 3i, and a rotation frequency of the charged particles at the time is a synchrotron oscillation frequency.

[0024] The confinement is a function required because the charged particles that constitute the bunch 3 always have variations in kinetic energy. The variations in kinetic energy cause differences in time for the bunch 3 to arrive at the same position after one turn along the design orbit. Without the confinement, the time difference is increased for each turn, and the charged particles diffuse over the entire design orbit.

[0025] When positive and negative induced voltages are applied to opposite ends of the bunch 3, energy is transferred to particles delayed in revolution because of insufficient energy by the positive induced voltage, entering an energy excessive state, and energy is lost from charged particles advanced in revolution because of excessive energy by the negative induced voltage, entering an energy insufficient state.

[0026] Thus, the particles delayed in revolution are advanced, while the particles advanced in revolution are delayed, thereby allowing the bunch 3 to be localized in a certain area in the advancing axis direction. The series of operations is referred to as the confinement of the bunch 3.

[0027] The function of the induction accelerating cell for confinement is thus equal to the separated function of confinement of the conventional rf acceleration cavity.

[0028] The devices for confinement have the function of reducing the length of the charged particle beam injected from an injection device into the synchrotron using the induction accelerating cell to be formed into the bunch 3 having a certain length so that the charged particle beam can be accelerated by another induction accelerating cell with a predetermined induced voltage having a different polarity or changing the length of the bunch 3 in various ways, and the function of providing phase stability to the bunch 3 during acceleration.

[0029] The devices for acceleration have the function of providing the induced voltage for acceleration 18 to the entire bunch 3 after the formation of the bunch 3.

[0030] In the conventional rf synchrotron, a phenomenon is known in which radio frequency waves unpredictable in a design stage are applied to the bunch 3 from devices that constitute the rf synchrotron. This phenomenon is referred to as disturbance. The disturbance is electromagnetic waves generated by the devices that constitute the synchrotron, and applied to the bunch 3 as a constant rf frequency depending on installation states for each acceleration.

[0031] When the frequency of the synchrotron oscillation 3i of the bunch 3 matches or becomes integer times the

frequency of the disturbance, resonance with the synchrotron oscillation 3i is induced, the charged particles are displaced from ideal energy, and the bunch 3 diffuses in the advancing axis direction, exceeds the time width of the acceleration area 36a of the radio frequency waves 36 and is lost. Similarly, when the induction accelerating cell for acceleration is used for accelerating the charged particle beam, the bunch 3 exceeds the length of the charging time period 18e of the acceleration voltage 18a and is lost.

[0032] For example, the charged particles in the bunch head 3d receive the rf acceleration voltage in a direction opposite to the acceleration direction, cannot be synchronized with the magnetic field excitation pattern of the synchrotron, collide with a wall surface of the vacuum duct and are lost.

[0033] In the acceleration of the charged particles, the loss of the particles reduces acceleration efficiency, and also causes a significant problem of activation of a spot of the collision with the wall surface of the vacuum duct to no small extent because any charged particles have high energy.

[0034] Thus, in conventional acceleration of charged particles, a synchrotron oscillation frequency is controlled by an amplitude changing device that can change the amplitude of radio frequency waves to avoid a match with the frequency of disturbance for preventing loss of charged particles by the disturbance.

[0035] Thus, the charged particle beam cannot be actually accelerated by the induced voltage without controlling the synchrotron oscillation frequency.

[0036] Figure 18 shows an example of a forming process of a super-bunch by a conventional induced voltage. For forming the super-bunch 3m, it is necessary to inject the bunch 3 into the vacuum duct multiple times and connect multiple bunches 3.

[0037] In Figure 18(A), a method of injecting the multiple bunches 3, and then connecting a further bunch 3 to a temporally long bunch 3o constituted by the bunches 3 successively connected before acceleration will be described. The super-bunch 3m is formed after the injection of the multiple bunches 3 and before confinement and acceleration of each bunch 3 with the barrier voltages 17.

[0038] The negative barrier voltage 17a and the positive barrier voltage 17b are applied to the bunch head 3d and the bunch tail 3e, respectively, of the bunch 3o to perform confinement for each turn. At this time, generation timing of the barrier voltages 17 is constant.

[0039] To the bunch 3 to be connected to the bunch 3o, negative and positive barrier voltages 17a and 17b are applied by an induction accelerating cell for movement separate from the induction accelerating cell for confinement, and the bunch 3 is brought close to the bunch 3o while being confined. For bringing the bunch 3 close to the bunch 3o, generation timing of a barrier voltage for movement 17g is gradually advanced.

[0040] This shortens a time duration between generations of the barrier voltage 17 used only for confinement and the barrier voltage for movement 17g (hereinafter referred to as a time duration between barrier voltage pulses 17h), and the bunch 3 is brought close to the bunch 3o (in the direction of the open arrow in the drawing) for each turn.

[0041] Finally, the positive barrier voltage of the bunch 3o is generated in a position corresponding to the bunch tail 3e of the bunch 3 to integrally connect the bunch 3o and the bunch 3. It has been considered that the super-bunch 3m is thus formed (Figure 18(B)).

[0042] It has been considered that the super-bunch 3m thus formed can be confined by the barrier voltages 17 including the negative barrier voltage 17a and the positive barrier voltage 17b, and accelerated by the induced voltage for acceleration 18 applied from the induction accelerating cell for acceleration separate from the induction accelerating cell for confinement.

[0043] However, the conventional acceleration of the charged particle beam by the induced voltage requires combination of induction accelerating cells and devices for controlling generation timing of induced voltages applied by the induction accelerating cells for each function of the induced voltages. For example, required combinations include an induction accelerating cell for acceleration, an induction accelerating cell for confinement, an induction accelerating cell for movement, an induction accelerating cell for synchrotron oscillation frequency control, and an induction accelerating cell for charged particle beam orbit control, and devices for controlling induced voltages applied by the induction accelerating cells.

[0044] Thus, each of the induced voltages needs to be controlled, which is complicated. Also, the combinations of the induction accelerating cells having respective functions and the devices for controlling the generation timing of the induced voltages applied by the induction accelerating cells need to be prepared, which increases construction costs of the accelerator.

[0045] Thus, the present invention has a first object to provide an induction accelerating cell for controlling acceleration of a charged particle beam and a set of induction accelerating device for controlling generation timing of an induced voltage applied by the induction accelerating cell in a synchrotron.

[0046] The present invention has a second object to provide an acceleration method of a charged particle beam by induced voltages having the same pulse shape, by using the induction accelerating device to control generation timing of the induced voltage.

[0047] The present invention has a third object to provide an accelerator that can accelerate arbitrary charged particles

up to an arbitrary energy level permitted by magnetic field strength of a bending magnet that constitutes a synchrotron using an induction accelerating cell (hereinafter referred to as an arbitrary energy level) with one accelerator, by using the induction accelerating device.

5 Disclosure of the Invention

[0048] In order to solve the above described problems, first, the present invention provides an induction accelerating device 5 in a synchrotron 1, including: an induction accelerating cell 6 that applies an induced voltage 8; a switching power supply 5b that supplies a pulse voltage 6f to the induction accelerating cell 6 via a transmission line 5a and drives the induction accelerating cell 6; a DC power supply 5c that supplies electric power to the switching power supply 5b; and an intelligent control device 7 including a pattern generator 13 that generates a gate signal pattern 13a for controlling on/off the switching power supply 5b, and a digital signal processing device 12 that controls on/off a gate master signal 12a that becomes the basis of the gate signal pattern 13a, a plurality of the induction accelerating cells 6 being provided according to the functions, characterized in that the digital signal processing device 12 includes: a variable delay time calculator 20 that stores a required variable delay time pattern 14b corresponding to an ideal variable delay time pattern 14a calculated on the basis of magnetic field excitation patterns 15 and 24, and generates a variable delay time signal 20a on the basis of the required variable delay time pattern 14b; a variable delay time generator 21 that receives a passage signal 9a of a bunch 3 from a bunch monitor 9 placed on a design orbit 2 along which a charged particle beam circulates and the variable delay time signal 20a from the variable delay time calculator 20 to generate a pulse 21a corresponding to a variable delay time 14; an induced voltage arithmetic unit 22 that stores an equivalent acceleration voltage value pattern 18j corresponding to an ideal acceleration voltage value pattern 18f calculated on the basis of the magnetic field excitation patterns 15 and 24, and receives the pulse 21a corresponding to the variable delay time 14 from the variable delay time generator 21 to generate a pulse 22a for controlling on/off the induced voltage 8; and a gate master signal output device 23 that receives the pulse 22a from the induced voltage arithmetic unit 22 to generate the gate master signal 12a that is a pulse suitable for the pattern generator 13, and outputs the gate master signal 12a after a lapse of the variable delay time 14. The variable delay time calculator 20 calculates the variable delay time 14 in real time on the basis of a beam deflection magnetic field strength signal 4b for indicating magnetic field strength of a bending magnet 4 that constitutes the synchrotron 1, and a revolution frequency of the charged particle beam on the design orbit 2, and generates the variable delay time signal 20a on the basis of the variable delay time 14, and the induction accelerating device 5 controls generation timing of the induced voltage 8.

[0049] Second, the present invention provides an acceleration method of a charged particle beam in a synchrotron 1, characterized by including the steps of: controlling generation timing of induced voltages 8 including a positive induced voltage 8a and a negative induced voltage 8b applied from a set of induction accelerating device 5; intermittently applying the induced voltages; and thus temporally separating functions of a barrier voltage 17 for confinement of a charged particle beam in an advancing axis direction 3a and an induced voltage for acceleration 18 for accelerating the charged particle beam.

[0050] Third, the present invention provides an accelerator 26 for accelerating arbitrary charged particles up to an arbitrary energy level, characterized by including: an injection device 29 including an ion source 30 that generates charged particles, a preinjector 31 that accelerates the charged particles up to a certain energy level, and an injector 32 that injects a charged particle beam accelerated by the preinjector 31 into an annular vacuum duct 2a having a design orbit 2 therein; an induction synchrotron 27 including a bending magnet 4 that is provided on a curved portion of the design orbit 2 and ensures the design orbit 2 of the charged particle beam (a bunch 3), a focusing electromagnet 28 that is provided on a linear portion of the design orbit 2 and ensures strong focusing of the charged particle beam, a bunch monitor 9 that is provided in the vacuum duct 2a and detects passage of the charged particle beam, and an induction accelerating device 5 connected to the vacuum duct 2a for controlling acceleration of the charged particle beam; and an extraction device 33 including an extractor 34 that extracts the charged particle beam accelerated up to a predetermined energy level by the induction synchrotron 27 to a beam utility line 35, and a transport pipe 34a, wherein the induction accelerating device 5 includes: an induction accelerating cell 6 that applies an induced voltage 8; a switching power supply 5b that supplies a pulse voltage 6f to the induction accelerating cell 6 via a transmission line 5a and drives the induction accelerating cell 6; a DC power supply 5c that supplies electric power to the switching power supply 5b; and an intelligent control device 7 including a pattern generator 13 that generates a gate signal pattern 13a for controlling on/off the switching power supply 5b, and a digital signal processing device 12 that controls on/off a gate master signal 12a that becomes the basis of the gate signal pattern 13a, a plurality of the induction accelerating cells 6 being provided according to functions, wherein the digital signal processing device 12 includes: a variable delay time calculator 20 that stores a required variable delay time pattern 14b corresponding to an ideal variable delay time pattern 14a calculated on the basis of magnetic field excitation patterns 15 and 24, and generates a variable delay time signal 20a on the basis of the required variable delay time pattern 14b; a variable delay time generator 21 that receives a passage signal 9a that is passage information of the bunch 3 from the bunch monitor 9 placed on the design orbit 2 along which a charged

particle beam circulates and the variable delay time signal 20a from the variable delay time calculator 20 to generate a pulse 21a corresponding to a variable delay time 14; an induced voltage arithmetic unit 22 that stores an equivalent acceleration voltage value pattern 18j corresponding to an ideal acceleration voltage value pattern 18f calculated on the basis of the magnetic field excitation patterns 15 and 24, and receives the pulse 21a corresponding to the variable delay time 14 from the variable delay time generator 21 to generate a pulse 22a for controlling on/off the induced voltage 8; and a gate master signal output device 23 that receives the pulse 22a from the induced voltage arithmetic unit 22 to generate the gate master signal 12a that is a pulse suitable for the pattern generator 13, and outputs the gate master signal 12a after a lapse of the variable delay time 14, and the induction accelerating device 5 controls generation timing of the induced voltage 8, and wherein the preinjector 31 is an electrostatic accelerator, a linear induction accelerator, or a small-sized cyclotron.

[0051] Alternatively, the variable delay time calculator 20 calculates the variable delay time 14 in real time on the basis of a beam deflection magnetic field strength signal 4b for indicating magnetic field strength of the bending magnet 4 that constitutes the synchrotron 1, and a revolution frequency of the charged particle beam on the design orbit 2, and generates the variable delay time signal 20a on the basis of the variable delay time 14.

[0052] Alternatively, the induced voltage arithmetic unit 22 calculates an acceleration voltage value 18c in real time on the basis of the beam deflection magnetic field strength signal 4b for indicating the magnetic field strength of the bending magnet 4 that constitutes the synchrotron 1, receives the pulse 21a corresponding to the variable delay time 14 from the variable delay time generator 21 to generate the pulse 22a for controlling on/off an induced voltage for acceleration 18.

Brief Description of the Drawings

[0053] Figure 1 is a schematic view of a synchrotron using an induction accelerating cell including the present invention, Figure 2 is a sectional schematic diagram of the induction accelerating cell connected to a vacuum duct, Figure 3 is an equivalent circuit diagram of a switching voltage and the induction accelerating cell that constitute an induction accelerating device, Figure 4 illustrates a variable delay time, Figure 5 shows a relationship between an acceleration energy level and the variable delay time, Figure 6 shows a relationship between a slow cycling and an acceleration voltage, Figure 7 shows a control method of the acceleration voltage by changing the pulse density, Figure 8 shows an example of an acceleration method in a linear excitation area of intermittently applying an excessive induced voltage, Figure 9 is a block diagram of a digital signal processing device, Figure 10 shows a relationship between a rapid cycling and the acceleration voltage, Figure 11 shows an example (simulation) of an acceleration method of a charged particle beam according to the present invention, Figure 12 shows a generation pattern of an induced voltage in the simulation in Figure 11, Figure 13 shows a method (simulation) of forming a super-bunch by the acceleration method of a charged particle beam according to the present invention, Figure 14 shows an example of changing an induced voltage value using multiple induction accelerating cells, Figure 15 is a general block diagram of an accelerator including the induction accelerating device according to the present invention, Figure 16 shows an acceleration principle of a charged particle beam by induced voltages applied from conventional induction accelerating cells having different functions, Figure 17 shows synchrotron oscillation, and Figure 18 shows an example of a conventional forming process of a super-bunch by an induced voltage.

Best Mode for Carrying Out the Invention

[0054] An acceleration method of a charged particle beam of a synchrotron 1 is achieved characterized in that the method includes the steps of: controlling generation timing of induced voltages 8 including a positive induced voltage 8a and a negative induced voltage 8b applied from a set of induction accelerating device 5; intermittently applying the induced voltages; and thus temporally separating functions of a barrier voltage 17 for confinement of a charged particle beam in an advancing axis direction 3a and an induced voltage for acceleration 18 for accelerating the charged particle beam.

[0055] Now, an induction accelerating device and a control method thereof according to the present invention will be described in detail with reference to the accompanying drawings.

[0056] Figure 1 is a schematic view of a synchrotron using an induction accelerating cell including an induction accelerating device according to the present invention.

[0057] The synchrotron 1 using the induction accelerating cell 6 including the induction accelerating device 5 according to the present invention includes: a bending magnet 4 that ensures a design orbit 2 in a vacuum duct along which an injected bunch 3 circulates; a focusing magnet that ensures strong focusing; a bunch monitor 9 that detects various kinds of information on a charged particle beam during acceleration, a speed monitor 10, and a position monitor 11.

[0058] The induction accelerating device 5 includes: an induction accelerating cell 6 that is connected to the vacuum duct having the design orbit 2 therein along which the bunch 3 circulates, and applies, to positively charged particles,

induced voltages 8 having different functions including a negative barrier voltage 17a applied to a bunch head 3d in a direction opposite to an advancing axis direction 3a of the bunch 3, a positive barrier voltage 17b applied to a bunch tail 3e in the same direction as the advancing axis direction 3a of the bunch 3, an acceleration voltage 18a for acceleration in the advancing axis direction 3a, and a reset voltage 18b that has a different polarity from the acceleration voltage 18a and avoids magnetic saturation of the induction accelerating cell 6; a switching power supply 5b that supplies a pulse voltage 6f to the induction accelerating cell 6 via a transmission line 5a and is repeatedly operable; a DC power supply 5c that supplies electric power to the switching power supply 5b, an intelligent control device 7 that performs feedback control of on/off of the switching power supply 5b; and an induced voltage monitor 5d for checking the value of an induced voltage applied from the induction accelerating cell 6.

[0059] In the present invention, an induced voltage 8 in the same direction as the advancing axis direction 3a such as the positive barrier voltage 17b or the acceleration voltage 18a is a positive induced voltage 8a. An induced voltage 8 in the direction opposite to the advancing axis direction 3a such as the negative barrier voltage 17a or the reset voltage 18b is a negative induced voltage 8b. When negatively charged particles are accelerated, positive and negative signs of the induced voltages 8 are reversed.

[0060] The intelligent control device 7 in the present invention includes a pattern generator 13 that generates a gate signal pattern 13a for controlling on/off the switching power supply 5b, and a digital signal processing device 12 that calculates a gate master signal 12a that becomes the basis of the gate signal pattern 13a generated by the pattern generator 13.

[0061] The gate signal pattern 13a is a pattern for controlling the induced voltages 8 applied from the induction accelerating cell 6. The pattern includes a signal for determining charging time periods and generation timing of the induced voltages 8 in application of the induced voltages 8, and a signal for determining a rest time between the positive induced voltage 8a and the negative induced voltage 8b. Thus, the gate signal pattern 13a can be adjusted to the length of the bunch 3 to be accelerated.

[0062] The pattern generator 13 converts the gate master signal 12a into a combination of on and off of a current path of the switching power supply 5b.

[0063] The switching power supply 5b generally has a plurality of current paths, adjusts currents passing through branches thereof, and controls directions of the currents to generate positive and negative voltages in a load (herein the induction accelerating cell 6).

[0064] The induction accelerating cell 6 is the same as conventional induction accelerating cells for confinement and acceleration. However, the conventional induction accelerating cells for confinement and acceleration require devices for controlling generation timing of different induced voltages for applying induced voltages having different functions, while in the induction accelerating cell 6 in the present invention, generation timing of the induced voltages 8 having the same rectangular pulse shape including the barrier voltage 17 for confinement of the bunch 3 and the induced voltage for acceleration 18 for accelerating the bunch 3 is controlled using one intelligent control device 7.

[0065] Figure 2 is a sectional schematic diagram of the induction accelerating cell connected to the vacuum duct. The induction accelerating cell 6 has the same structure in principle as an induction accelerating cell for a linear induction accelerator constructed heretofore.

[0066] The induction accelerating cell 6 has a double structure of an inner cylinder 6a and an outer cylinder 6b, and a magnetic material 6c is inserted into the outer cylinder 6b to produce an inductance. Part of the inner cylinder 6a connected to the vacuum duct 2a in which the bunch 3 circulates is made of an insulator 6d such as ceramic.

[0067] When a pulse voltage 6f is applied from the DC power supply 5c connected to the switching power supply 5a to a primary side electric circuit surrounding the magnetic material 6c, a primary current 6g (core current) flows through a primary side conductor. The primary current 6g generates a magnetic flux around the primary side conductor to excite the magnetic material 6c surrounded by the primary side conductor.

[0068] This temporally increases the density of the magnetic flux passing through the magnetic material 6c of toroidal shape. During this time period, the electric field is induced according to Faraday's induction law in an insulator portion on a secondary side including opposite ends 6h of the inner cylinder 6a of the conductor with the insulator 6d in between. The induced electric field becomes an electric field 6e.

[0069] A portion where the electric field 6e is produced is an acceleration gap 6i. Thus, the induction accelerating cell is equivalent to a one-to-one transformer. Since the induction accelerating cell 6 generates heat in use, cooling oil or the like is circulated in the outer cylinder 6b in some cases, which requires an insulator seal 6j.

[0070] The switching power supply 5b that generates the pulse voltage 6f is connected to the primary side electric circuit of the induction accelerating cell 6, and the switching power supply 5b is externally turned on/off to freely control the production of the acceleration electric field.

[0071] Figure 3 is an equivalent circuit diagram of a switching voltage and the induction accelerating cell that constitute the induction accelerating device. In the equivalent circuit, the switching power supply 5b always charged by the DC power supply 5c connects to the induction accelerating cell 6 via the transmission line 5a.

[0072] The induction accelerating cell 6 includes a parallel circuit of an induction component L, a capacity component

C, and a resistance component R. The voltage across the parallel circuit is the induced voltage 8 applied to the bunch 3.

[0073] In the circuit in Figure 3, a first switch 5g and a fourth switch 5j are turned on by the gate signal pattern 13a, a voltage charged in a bank capacitor 5f is applied to the induction accelerating cell 6, and the positive induced voltage 8a that functions as the acceleration voltage 18a is generated in an acceleration gap 6i.

[0074] The positive induced voltage 8a that functions as the positive barrier voltage 17b for confinement of the bunch 3 in the acceleration gap 6i is similarly applied. However, there are differences in generation timing, and in that the acceleration voltage 18a is applied to the entire bunch 3 while the positive barrier voltage 17b is applied to the bunch tail 3e.

[0075] Then, the first switch 5g and the fourth switch 5j are turned off by the gate signal pattern 13a. At this time, the induced voltage 8 is off.

[0076] Next, a second switch 5h and a third switch 5i are turned on by the gate signal pattern 13a, and the negative induced voltage 8b that functions as the reset voltage 18b is generated. The generation timing is limited in a time period without the bunch 3.

[0077] The negative induced voltage 8b that functions as the negative barrier voltage 17a in the direction opposite to the positive induced voltage 8a for confinement of the bunch 3 in the acceleration gap 6i is similarly applied, and the magnetic saturation of the magnetic material 6c of the induction accelerating cell 6 that has occurred in the generation of the positive induced voltage 8a is reset.

[0078] Similarly, the first switch 5g and the fourth switch 5j that have been turned on are turned off by the gate signal pattern 13a. Also at this time, the induced voltage 8 is off.

[0079] The first switch 5g and the fourth switch 5j are again turned on by the gate signal pattern 13a. The series of switching operations are repeated by the gate signal pattern 13a to allow confinement and movement of the bunch 3, control of the orbit of the charged particle beam, control of a synchrotron oscillation frequency, and acceleration of the charged particle beam.

[0080] The gate signal pattern 13a is a signal for controlling driving of the switching power supply 5b, and is digitally controlled by the intelligent control device 7 including the digital signal processing device 12 and the pattern generator 13 on the basis of the passage signal 9a of the bunch 3 from the bunch monitor 9.

[0081] The induced voltage 8 applied to the bunch 3 is equal to a value calculated from the product of a current value and matching resistance 5k in the circuit. Thus, the current value can be measured by an ammeter that is the induced voltage monitor 5d to check the value of the applied induced voltage 8.

[0082] Thus, the value of the induced voltage 8 obtained from the induced voltage monitor 5d can be fed back to the digital signal processing device 12 as the induced voltage signal 5e and used for next generation of the gate master signal 12a.

[0083] In order to accelerate the charged particle beam by the induced voltage 8 controlled by the set of induction accelerating device 5, it is necessary to control the synchrotron oscillation frequency, control the generation timing of the induced voltage 8 so as to match the passage of the bunch 3, and apply an acceleration voltage value 18c synchronized with a magnetic field excitation pattern.

[0084] The synchrotron oscillation frequency control can be realized by applying the positive and negative induced voltages 8a and 8b that function as the barrier voltages 17 to the bunch 3 besides providing phase stability.

[0085] To control the generation timing of the induced voltage 8, it is necessary to synchronize the generation timing with the passage of the bunch 3.

[0086] Further, the charged particle beam during acceleration changes in the number of turns (a revolution frequency (f_{REV})) along the design orbit 2 per unit time with the passage of acceleration time. For example, when a proton beam is accelerated by a 12 GeV proton rf synchrotron (hereinafter referred to as 12GeVPS) by High energy accelerator research organization (hereinafter referred to as KEK), the revolution frequency of the proton beam changes from 667 kHz to 882 kHz.

[0087] Since an accelerator including the synchrotron 1 using the induction accelerating cell 6 is installed in a broad site, long cables including signal wires connecting the devices that constitute the accelerator need to be routed. The speed of signals transmitted through the signal wires is finite.

[0088] Thus, if the configuration of the accelerator is changed, time for the signals to pass through each device is not necessarily the same as before the change. Thus, in the accelerator including the synchrotron 1 using the induction accelerating cell 6, timing of charging time periods 8c and 8d need to be reset for each change of components.

[0089] Then, a variable delay time is used. Now, the variable delay time will be described. Figure 4 illustrates a variable time. The variable delay time 14 is a time period between generation of the passage signal 9a from the bunch monitor 9 and application of the induced voltage 8, which is adjusted by the digital signal processing device 12 for controlling the generation timing of the induced voltage 8 according to the position of the bunch 3 on the design orbit 2.

[0090] At an acceleration stage of the charged particle beam, the generation timing is controlled so that the negative induced voltage 8b that functions as the negative barrier voltage 17a is applied to the bunch head 3d, the positive induced voltage 8a that functions as the positive barrier voltage 17b is applied to the bunch tail 3e, the positive induced voltage 8a that functions as the acceleration voltage 18a is applied to the entire bunch 3, and the negative induced voltage 8b

that functions as the reset voltage 18b is applied in a time period when no bunch 3 exists in the induction accelerating cell 6.

[0091] Specifically, in the digital signal processing device 12, a time period between receiving the passage signal 9a from the bunch monitor 9 and the generation of the gate master signal 12a is controlled.

[0092] Δt that represents the variable delay time 14 is calculated by the following formula (1):

$$\Delta t = t_0 - (t_1 + t_2) \dots \text{Formula (1)}$$

where t_0 is a movement time 3b of the bunch 3 from the bunch monitor 9 placed on the design orbit 2 to the induction accelerating cell 6, t_1 is a transmission time of the passage signal 9a from the bunch monitor 9 to the digital signal processing device 12, and t_2 is a transmission time required for applying the induced voltage 8 by the induction accelerating cell 6 on the basis of the gate master signal 12a output from the digital signal processing device 12.

[0093] For example, if the movement time 3b (t_0) of the bunch 3 from the bunch monitor 9 to the induction accelerating cell 6 at a certain acceleration stage is 1 μsec , the transmission time t_1 of the passage signal 9a is 0.2 μsec , and the transmission time t_2 required between the generation of the gate master signal 12a and the generation of the induced voltage 8 is 0.3 μsec , the variable delay time 14 is 0.5 μsec .

[0094] Δt changes with acceleration because to changes with acceleration of the bunch 3. Thus, to control the generation timing of the induced voltage 8 according to the position of the bunch 3 and apply the induced voltage 8 to the bunch 3, Δt needs to be calculated for each turn of the bunch 3. On the other hand, t_1 and t_2 are constant once the devices that constitute the synchrotron 1 using the induction accelerating cell 6 are installed.

[0095] t_0 can be calculated from the revolution frequency ($f_{\text{REV}}(t)$) of the bunch 3 and a length (L) of the design orbit 2 along which the bunch 3 moves from the bunch monitor 9 to the induction accelerating cell 6, or may be actually measured.

[0096] Now, a method of calculating to from the revolution frequency ($f_{\text{REV}}(t)$) of the bunch 3 will be described. t_0 can be calculated in real time by the following formula (2):

$$t_0 = L / (f_{\text{REV}}(t) \cdot C_0) \text{ [sec]} \dots \text{Formula (2)}$$

where C_0 is the entire length of the design orbit 2 along which the bunch 3 circulates. $f_{\text{REV}}(t)$ is calculated by the following formula (3):

$$f_{\text{REV}}(t) = \beta(t) \cdot c / C_0 \text{ [Hz]} \dots \text{Formula (3)}$$

wherein $\beta(t)$ is a relativistic particle speed, and c is the speed of light ($c = 2.998 \times 10^8 \text{ [m/s]}$). $\beta(t)$ is calculated by the following formula (4):

$$\beta(t) = \sqrt{1 - (1 / (\gamma(t)^2))} \text{ [dimensionless]} \dots \text{Formula (4)}$$

wherein $\gamma(t)$ is a relativistic coefficient. $\gamma(t)$ is calculated by the following formula (5):

$$\gamma(t) = 1 + \Delta T(t) / E_0 \text{ [dimensionless]} \dots \text{Formula (5)}$$

wherein $\Delta T(t)$ is an increment of energy transferred by the acceleration voltage 18a, and E_0 is the static mass of the charged particles. $\Delta T(t)$ is calculated by the following formula (6):

$$\Delta T = p \cdot C_0 \cdot e \cdot \Delta B(t) \text{ [eV]} \dots \text{Formula (6)}$$

wherein p is a radius of curvature of the bending magnet 4, C_0 is the entire length of the design orbit 2 along which the bunch 3 circulates, e is an amount of charge of the charged particles, and $\Delta B(t)$ is an increment of beam deflection magnetic field strength from the start of acceleration.

[0097] The static mass (E_0) of the charged particles and the amount of charge (e) of the charged particles are different depending on the kinds of the charged particles.

[0098] Thus, the variable delay time 14 is uniquely determined by the revolution frequency of the bunch 3 if a distance (L) between the bunch monitor 9 and the induction accelerating cell 6 and the entire length (C_0) of the design orbit 2 along which the bunch 3 circulates are determined. The revolution frequency of the bunch 3 is also uniquely determined by the magnetic field excitation pattern.

[0099] The variable delay time 14 required at a certain acceleration time is also uniquely determined if the kind of the charged particles and setting of the synchrotron 1 using the induction accelerating cell 6 are determined. Thus, if it is supposed that the bunch 3 is ideally accelerated according to the magnetic field excitation pattern, the variable delay time 14 may be previously calculated by the definition formulas.

[0100] The series of formulas for calculating the variable delay time 14 (Δt) are referred to as definition formulas, and the definition formulas are provided to a variable delay time calculator 20 described later of the digital signal processing device 12 in calculating the variable delay time 14 (Δt) in real time.

[0101] The variable delay time 14 thus provided is output to a variable delay time generator 21 as a variable delay time signal 20a that is digital data described later.

[0102] Figure 5 shows a relationship between an acceleration energy level and the variable delay time. The graph in Figure 5 shows a relationship between an energy level of a proton beam and an output time of the variable delay time 14. Data in Figure 5 are values when a proton beam is injected into KEK 12GeVPS.

[0103] The axis of abscissa MeV represents the energy level of the proton beam, and the unit is megavolt. One MeV is one million electronic volts and corresponds to 1.602×10^{-13} joules.

[0104] The axis of ordinate Δt (μs) represents the delay of output timing (variable delay time 14) of the gate signal pattern 13a for controlling the acceleration voltage 18a generated by the induction accelerating cell 6 with the time of the passage of the bunch 3 through the bunch monitor 9 as zero, and the unit is microsecond. The variable delay time 14 receives the passage signal 9a from the bunch monitor 9 and is controlled by the digital signal processing device 12 as described above.

[0105] The energy level of the proton beam is uniquely determined by the revolution speed of the proton beam. The revolution speed of the proton beam is synchronized with the magnetic field excitation pattern of the synchrotron 1. Thus, the variable delay time 14 can be previously calculated from the revolution speed or the magnetic field excitation pattern rather than is calculated in real time.

[0106] The graph in Figure 5 shows an ideal variable delay time pattern 14a and a required variable delay time pattern 14b corresponding to the ideal variable delay time pattern 14a.

[0107] The ideal variable delay time pattern 14a refers to a variable delay time 14 corresponding to changes in energy level and required in a time period between the passage of the bunch 3 through the bunch monitor 9 and output of the gate master signal 12a by the digital signal processing device 12 if adjusted for each turn of the bunch 3 of the proton beam for applying the acceleration voltage 18a according to changes in revolution speed of the bunch 3.

[0108] The required variable delay time pattern 14b refers to a variable delay time 14 corresponding to changes in energy level in which the acceleration voltage 18a can be applied to the bunch 3, like the ideal variable delay time pattern 14a.

[0109] It is ideally desirable that the variable delay time 14 is calculated and controlled for each turn of the bunch 3, but the required variable delay time pattern 14b that is a stepwise variable delay time 14 may be provided because the highest control accuracy of a pulse 21a of the variable delay time generator 21 corresponding to the variable delay time 14 achieved by the current technique is $\pm 0.01 \mu s$, and sufficiently efficient acceleration can be performed without loss of charged particles even if the variable delay time 14 is not calculated and controlled for each turn of the bunch 3.

[0110] Thus, the variable delay time 14 is controlled by a certain time unit. This unit is referred to as a control time unit 14c, and herein $0.1 \mu s$.

[0111] In the graph in Figure 5(A), the proton beam immediately after injection 16a with a low energy level requires a variable delay time 14 of about $1.0 \mu s$ in acceleration of KEK 12GeVPS.

[0112] Further, the energy level of the proton beam increases with acceleration time, which reduces the variable delay time 14. Particularly, in a region from about 4500 MeV to near the finish of acceleration, the variable delay time 14 approaches zero.

[0113] Thus, in the synchrotron 1 using the induction accelerating cell 6, the induction accelerating device 5 according to the present invention is used to allow arbitrary charged particles with arbitrary revolution frequency to be easily accelerated up to an arbitrary energy level, by replacing an equivalent acceleration voltage value pattern 18j calculated from a magnetic field excitation pattern by the variable delay time calculator 20 described later with a magnetic field excitation pattern corresponding to selected charged particles, or with the required variable delay time pattern 14b

corresponding to the ideal variable delay time pattern 14a calculated from the magnetic field excitation pattern.

[0114] Figure 6 shows a relationship between a slow cycling and an acceleration voltage. Figure 6 shows a magnetic field excitation pattern 15 in acceleration of the proton beam by the KEK 12GeVPS.

[0115] The axis of abscissa t represents an operating time with reference to a time when the charged particle beam is injected 16a into the synchrotron 1 using the induction accelerating cell 6. The first axis of ordinate B represents magnetic field strength of the bending magnet 4 that constitutes the synchrotron 1 using the induction accelerating cell 6. The second axis of ordinate v represents the acceleration voltage value 18c.

[0116] The slow cycling refers to acceleration by the magnetic field excitation pattern 15 of the synchrotron 1 with slow cycling of one cycle 16 of about several seconds, one cycle starting from a time when the charged particles are injected 16a from a preinjector, and going through an acceleration time 16c and extraction 16b to the next injection 16a.

[0117] The magnetic field excitation pattern 15 is gradually increased in magnetic field strength immediately after the injection 16a of the charged particle beam, and enters the maximum magnetic field excitation state at the time of the extraction 16b. Particularly, the magnetic field strength is exponentially increased immediately after the injection 16a of the charged particle beam. The magnetic field excitation pattern 15 in this time period is referred to as a nonlinear excitation area 15a. Then, the magnetic field strength is linear-functionally increased until the finish of the acceleration 16d. The magnetic field excitation pattern 15 in this time period is referred to as a linear excitation area 15b.

[0118] Thus, to accelerate the charged particle beam with the synchrotron 1 using the induction accelerating cell 6, it is necessary to generate the positive induced voltage 8a that functions as the acceleration voltage 18a in synchronization with the magnetic field excitation pattern 15.

[0119] An ideal acceleration voltage value 18c (V_{acc}) synchronized with the magnetic field excitation pattern 15 of the synchrotron 1 has a relationship as expressed in the following formula (7).

$$V_{acc} \propto dB/dt \dots \text{Formula (7)}$$

The ideal acceleration voltage value 18c thus calculated is referred to as an ideal acceleration voltage value pattern 18f. A reset voltage value 18d in an opposite sign to the ideal acceleration voltage value pattern 18f is referred to as an ideal reset voltage value pattern 18g.

[0120] Specifically, a required acceleration voltage value 18c in a certain time is proportional to the time rate of change of the magnetic field excitation pattern 15 in the time. Thus, in the nonlinear excitation area 15a, the magnetic field strength is quadratically increased, and a required acceleration voltage value 18i changes linearly in proportional to the changes in the acceleration time 16c.

[0121] On the other hand, an ideal acceleration voltage value 18h in the linear excitation area 15b is constant irrespective of the changes in the acceleration time 16c.

[0122] Since the acceleration voltage 18a cannot be continuously applied as described above, the reset voltage 18b needs to be applied after the acceleration voltage 18a.

[0123] Thus, to synchronize the acceleration voltage 18a with the magnetic field excitation pattern 15 of the nonlinear excitation area 15a, it is necessary to increase the acceleration voltage value 18c with time changes. However, the induction accelerating cell 6 itself includes no adjustment mechanism of the induced voltage value, and thus an acceleration voltage value 18c of a constant value only can be obtained.

[0124] On the other hand, it is supposed that a charging voltage of the bank capacitor 5f generated by the induction accelerating cell 6 is controlled to change the acceleration voltage value 18c. However, the bank capacitor 5f is originally provided for controlling changes in charging voltage with output changes, and thus the method of changing the charging voltage of the bank capacitor 5f cannot be actually used for quickly controlling the acceleration voltage value 18c.

[0125] Thus, pulse density in Figure 7 is adopted, and the induction accelerating device 5 is used to synchronize the generation timing of the acceleration voltage 18a with the magnetic field excitation pattern 15 of the nonlinear excitation area 15a.

[0126] Figure 7 shows a control method of the acceleration voltage by changing the pulse density. Figure 7(A) is an enlarged view of part of the acceleration time 16c in Figure 6. Reference characters t , B and V represent the same as in Figure 6.

[0127] Figure 7(B) shows pulse density 19 of the induced voltage for acceleration 18 in a certain number of turns of the bunch 3 in the linear excitation area 15b in Figure 7(A). Figure 7(C) shows pulse density 19 in the nonlinear excitation area 15a in Figure 7(A).

[0128] A group of generation timing of the induced voltage for acceleration 18 is referred to as the pulse density 19. The number of turns of the bunch 3 for controlling the pulse density 19 every certain number of turns is herein referred to as a unit of control 15c.

[0129] To accelerate the proton beam in synchronization with the significantly changing magnetic field excitation

pattern 15, first, it is necessary that the induction accelerating cell 6 that can apply the acceleration voltage value 18h required in the linear excitation area 15b can apply the acceleration voltage 18a that is a constant voltage value for each turn of the proton beam.

[0130] For example, when the acceleration voltage value 18h required in the linear excitation area 15b is 4.7 kV from the relationship in Formula (7), an induction accelerating cell 6 that can apply the acceleration voltage 18a of 4.7 kV or more is required. The pulse density 19 at that time is shown in Figure 7(B).

[0131] Figure 7(B) shows that the acceleration voltage value 18h required in the linear excitation area 15b in Figure 7(A) is 4.7 kV, and thus adjustment is made so that the acceleration voltage 18a of 4.7 kV is applied for each turn of the bunch 3, and the reset voltage 18b is applied.

[0132] Next, it is necessary to provide the ideal acceleration voltage value pattern 18f to the bunch 3 for synchronization with the nonlinear excitation area 15a. For this purpose, even with the induction accelerating cell 6 that can apply only the acceleration voltage 18a of a constant value, the number of times of application of the acceleration voltage 18a is adjusted in the unit of control 15c to allow an acceleration voltage value 18c equivalent to the ideal acceleration voltage value pattern 18f to be provided.

[0133] Specifically, the number of times of application of the acceleration voltage 18a in the unit of control 15c is increased stepwise from zero to the application for each turn of the bunch 3, and thus the acceleration voltage value 18c equivalent to the ideal acceleration voltage value pattern 18f can be provided in a certain time. The group of the equivalent acceleration voltage values 18c is referred to as an equivalent acceleration voltage value pattern 18j.

[0134] For example, when the maximum value of the acceleration voltage value 18i required in the nonlinear excitation area 15a is 4.7 kV, and the unit of control 15c of the acceleration voltage 18a is 10 turns, the acceleration voltage value 18i can be adjusted stepwise at 0.47 kV intervals from 0 kV to 4.7 kV. Thus, the equivalent acceleration voltage value pattern 18j in the nonlinear excitation area 15a can be divided into 10 stages. The pulse density 19 at that time is shown in Figure 7(C).

[0135] Figure 7(C) shows an example of a control method of pulse density 19 when the equivalent acceleration voltage value 18i is 0.97 kV in the nonlinear excitation area 15a. When the number of turns of the bunch 3 in the unit of control 15c is 10, the acceleration voltage 18a at the constant value of 4.7 kV is applied at any two turns among the 10 turns.

[0136] Specifically, the acceleration voltage 18a and the reset voltage 18b shown by the solid lines in Figure 7(C) may be generated. The voltages can be generated by stopping application of induced voltages for acceleration 18k and reset voltages 18l shown by the dotted lines in real time.

[0137] The generation timing of the acceleration voltage 18a is thus controlled to apply the voltage of 0.97 kV that is the equivalent acceleration voltage value 18i. After the acceleration voltage 18a, the reset voltage 18b is naturally required.

[0138] When an acceleration voltage value 18i smaller than 0.47 kV is required, it is only necessary to adjust the ratio of the number of times of application of the acceleration voltage 18a to the number of turns of the bunch 3. For example, when an acceleration voltage value 18i of 0.093 kV is required, it is only necessary to apply the acceleration voltage 18a twice every 100 turns of the bunch 3.

[0139] When the nonlinear excitation area 15a lasts for 0.1 seconds, a time period for each step with the unit of control 15c being set to 10 is 0.01 seconds.

[0140] Specifically, the adjustment of the acceleration voltage value 18c by controlling the pulse density 19 is allowed by performing control to stop generation of the gate signal pattern 13a with the intelligent control device 7 including the digital signal processing device 12 and the pattern generator 13 on the basis of the passage signal 9a from the bunch monitor 9.

[0141] An acceleration voltage value (V_{ave}) applied to the bunch 3 in the unit of control 15c is calculated by the following formula (8) from an acceleration voltage value 18c (V_0) of a constant value applied by the induction accelerating cell 6, the number of times of application (Non) of the acceleration voltage 18a in the unit of control 15c, and the number of times of turn-off of the acceleration voltage 18a (Noff):

$$V_{ave} = V_0 \cdot \text{Non} / (\text{Non} + \text{Noff}) \quad \dots \text{Formula (8)}$$

[0142] Specifically, the induction accelerating device 5 according to the present invention is used to adjust the pulse density 19 in the unit of control 15c by the above described method, and even with the induction accelerating cell 6 that can apply only the acceleration voltage 18a of a substantially constant voltage value (V_0), the equivalent acceleration voltage value pattern 18j corresponding to the ideal acceleration voltage value pattern 18f is provided to allow the acceleration voltage 18a to be applied to the charged particle beam in synchronization with the magnetic field excitation pattern 15 with slow cycling including the significantly changing nonlinear excitation area 15a.

[0143] The pulse density 19 may be previously provided to an induced voltage arithmetic unit 22 described later as the equivalent acceleration voltage value pattern 18j, or calculated by the induced voltage arithmetic unit 22 in real time.

[0144] A time period between the acceleration voltages 18a continuously applied (hereinafter referred to as a time duration between pulses 19a) is gradually reduced to accommodate a reduction in revolution time of the bunch 3.

[0145] Figure 8 shows an example of an acceleration method in the linear excitation area where an induced voltage of an excessive value is intermittently applied. The axis of abscissa t represents changes with time in the induction accelerating cell 6, and the axis of ordinate v represents the voltage value of the induced voltage 8. v_0 represents an induced voltage value applied from the induction accelerating cell 6.

[0146] In the pulse density 19 in Figure 7(A), only the induced voltage for acceleration 18 can be applied, and induced voltages 8 having other functions cannot be applied.

[0147] Then, the induction accelerating cell 6 that can apply an excessive induced voltage value in the linear excitation area 15b is used to intermittently apply the induced voltage for acceleration 18 even in the linear excitation area 15b, rather than apply the induced voltage for acceleration 18 for each turn of the bunch 3. Herein, a method is shown of applying the induced voltage for acceleration 18 with certain continuous 10 turns of the bunch 3 in the linear excitation area 15b being the unit of control 15c.

[0148] In acceleration by the conventional induction accelerating cell for acceleration, the required acceleration voltage value 18c may be applied for each turn, while in the acceleration method of a charged particle beam according to the present invention, the barrier voltage 17 also needs to be applied from the induction accelerating cell 6 that applies the induced voltage for acceleration 18, and a time for applying the barrier voltage 17 needs to be ensured.

[0149] Thus, the acceleration voltage 18a of the excessive acceleration voltage value 18c is used even in the linear excitation area 15b to ensure the time for applying the barrier voltage 17. It has been found from diligent studies that there is no need for applying the barrier voltage 17 for each turn of the bunch 3.

[0150] The number of times of application of the barrier voltage 17 differs depending on the degree of diffusion of the charged particles that constitute the bunch 3, and the acceleration energy level.

[0151] The acceleration voltage 18a and the reset voltage 18b are applied to two turns among the 10 turns from the induction accelerating cell 6 that can apply an acceleration voltage value 18c about five times the acceleration voltage value 18h in the linear excitation area 15b. The application of the induced voltages for acceleration 18k and the reset voltages 18l shown by the dotted lines is stopped.

[0152] In the 10 turns in the unit of control 15c, an average acceleration voltage value 18c applied to the bunch 3 is substantially equivalent to the acceleration voltage 18a required in the linear excitation area 15b.

[0153] Thus, the induction accelerating cell 6 that can apply an excessive acceleration voltage value 18c is used even in the linear excitation area 15b, thereby eliminating the need for applying the induced voltage for acceleration 18 for each turn of the bunch 3, and ensuring the time for applying the induced voltages 8 having other functions.

[0154] Figure 9 is a block diagram of the digital signal processing device. The digital signal processing device 12 includes a variable delay time calculator 20, a variable delay time generator 21, an induced voltage arithmetic unit 22, and a gate master signal output device 23.

[0155] The variable delay time calculator 20 determines the variable delay time 14. Definition formulas of the variable delay time 14 calculated on the basis of information on the kind of charged particles and the magnetic field excitation patterns 15 and 24 are provided to the variable delay time calculator 20, which are a series of formulas (1) to (6) for calculating the variable delay time 14 described above, or the required variable delay time pattern 14b.

[0156] The information on the kind of charged particles is the mass and the charge state of the accelerated charged particles. Energy obtained by the charged particles from the induced voltage 8 is proportional to the charge state, and the speed of the charged particles thus obtained depends on the mass of the charged particles. Since changes in the variable delay time 14 depend on the speed of the charged particles, the information is previously provided.

[0157] The variable delay time generator 21 is a counter using a certain frequency as a reference, and keeps the passage signal 9a from the bunch monitor 9 in the digital signal processing device 12 for a certain time period and then causes the passage signal 9a to pass through. For example, with a counter of 1 kHz, the numerical value of 1000 of the counter is equal to 1 sec. Specifically, a numerical value corresponding to the variable delay time 14 can be input to the variable delay time generator 21 to control the length of the variable delay time 14.

[0158] Specifically, the variable delay time generator 21 performs control to stop generation of the gate master signal 12a for a time period corresponding to the variable delay time 14 on the basis of the variable delay time signal 20a that is output by the variable delay time calculator 20 and is a value corresponding to the variable delay time 14.

[0159] This allows the generation timing of the induced voltage 8 to match with the time when the bunch 3 arrives at the induction accelerating cell 6 or the time when no bunch 3 exists in the induction accelerating cell 6, and also allows an arbitrary time to be selected.

[0160] For example, if the variable delay time calculator 20 outputs a variable delay time signal 20a of the numerical value of 150 is output to the variable delay time generator 21 that is the counter of 1 kHz, the variable delay time generator 21 performs control to delay generation of a pulse 21a for 0.15 sec.

[0161] The variable delay time generator 21 receives the passage signal 9a from the bunch monitor 9 and the variable delay time signal 20a from the variable delay time calculator 20 to calculate timing for generating the next induced voltage

8 for each bunch 3 having passed through the bunch monitor 9, and outputs the pulse 21a that is information on the variable delay time 14 to the induced voltage arithmetic unit 22.

[0162] The passage signal 9a is a pulse generated at an instant of the passage of the bunch 3 through the bunch monitor 9. The pulse includes a voltage pulse, a current pulse, a light pulse, or the like having appropriate strength according to the kinds of media or cables that transmit the pulse. The bunch monitor 9 for obtaining the passage signal 9a may be a monitor for detecting passage of charged particles conventionally used in an rf synchrotron.

[0163] The passage signal 9a is used for providing passage timing of the bunch 3 as time information to the digital signal processing device 12. A position of the bunch 3 on the design orbit 2 in the advancing axis direction 3a is calculated by a leading edge of the pulse generated by the passage of the bunch 3. Specifically, the passage signal 9a is a reference of a start time of the variable delay time 14.

[0164] The induced voltage arithmetic unit 22 determines the kind of the induced voltage 8 and whether the induced voltage 8 is generated (on) or not (off).

[0165] For example, when a negative barrier voltage value 17c (positive barrier voltage value 17d) required at a certain instant is -0.5 kV (0.5 kV), the induced voltage arithmetic unit 22 determines whether a pulse 22a is generated (1) or not (0).

[0166] Using the negative barrier voltage 17a (positive barrier voltage 17b) of a constant value of -1.0 kV (1.0 kV), the induced voltage arithmetic unit 22 represents whether the negative barrier voltage 17a (or positive barrier voltage 17b) is applied or not as [1, 0, ..., 1] every 10 turns of the bunch 3.

[0167] If the induced voltage arithmetic unit 22 represents 1 five times and 0 five times, an average negative barrier voltage value (positive barrier voltage value) received by the bunch 3 during 10 turns is -0.5 kV (0.5 kV). Thus, the induced voltage arithmetic unit 22 can digitally control the induced voltage 8.

[0168] For example, when the negative barrier voltage value 17c (positive barrier voltage value 17d) is changed from 0 V to -1 kV (1 kV) in 1 sec and controlled at 0.1 sec intervals, an equivalent barrier voltage value pattern is a data table with such as 0 kV for 0.1 sec from the start of acceleration, -0.1 kV (0.1 kV) for 0.1 to 0.2 sec, - 0.2 kV (0.2 kV) for 0.2 to 0.3 ... -1.0 kV (1.0 kV) for 0.9 to 1.0 sec.

[0169] When the unit of control is n turns, and the acceleration voltage 18a is applied to the charged particle beam m times during the n turns, an equivalent acceleration voltage value received by the charged particle beam in the unit of control 15c is m/n times the acceleration voltage value 18c output by the induction accelerating cell 6.

[0170] It is clear that m is always smaller than n. This condition is met when the unit of control 15c is sufficiently shorter than the speed of change of the orbit of the charged particle beam. The unit of control 15c can be freely selected within a range from a lower limit where the unit of control 15c is reduced to reduce voltage accuracy to prevent an appropriate voltage from being applied and an upper limit where the unit of control 15c is increased to prevent response to the change of the orbit.

[0171] The voltage value of the induced voltage 8 required for a certain time can be calculated in real time for each turn of the bunch 3. When the voltage value of the induced voltage 8 required for a certain time is calculated in real time, it is only necessary that magnetic field strength at the time is received as a beam deflection magnetic field strength signal 4b from the bending magnet 4 that constitutes the synchrotron 1 using the induction accelerating cell 6, and the voltage value is calculated by a calculation formula similar to that in the case of previous calculation.

[0172] The pulse 22a that is determined on the basis of the voltage value of the induced voltage 8 required for a certain time during acceleration provided as described above and controls generation of the gate master signal 12a is output to the gate master signal output device 23.

[0173] The gate master signal output device 23 generates a pulse for transmitting the pulse 22a containing information on the variable delay time 14 of passage through the digital signal processing device 12 and on/of of the barrier voltage 17 to the pattern generator 13, that is, the gate master signal 12a.

[0174] The leading edge of the pulse that is the gate master signal 12a output from the gate master signal output device 23 is used as generation timing of the barrier voltage 17. The gate master signal output device 23 converts the pulse 22a output from the induced voltage arithmetic unit 22 into a voltage pulse, a current pulse, a light pulse, or the like having appropriate pulse strength according to the kinds of media or cables that transmit the pulse to the pattern generator 13.

[0175] Like the passage signal 9a, the gate master signal 12a is a rectangular voltage pulse output from the gate master signal output device 23 at the instant of the passage of the variable delay time 14 for generating the appropriate induced voltage 8 on the basis of the passage of the bunch 3. The pattern generator 13 recognizes the leading edge of the pulse that is the gate master signal 12a to start the operation.

[0176] The digital signal processing device 12 as described above outputs the gate master signal 12a that becomes the basis of the gate signal pattern 13a that controls driving of the switching power supply 5b to the pattern generator 13 on the basis of the passage signal 9a from the bunch monitor 9 on the design orbit 2 along which the bunch 3 circulates. Specifically, the digital signal processing device 12 controls on/off the induced voltage 8.

[0177] The variable delay time 14 and the voltage value and the charging time period of the induced voltage 8 are calculated in real time to allow the induced voltage 8 synchronized with the revolution frequency of the bunch 3 to be

applied according to the magnetic field excitation pattern 15 of the synchrotron 1 using the induction accelerating cell 6 without changing setting.

[0178] When the variable delay time 14 is previously calculated, the passage of the bunch 3 and the generation timing of the induced voltage 8 can be always matched with each other simply by replacing the required variable delay time pattern 14b corresponding to the ideal variable delay time pattern 14a in the variable delay time calculator 20 and the equivalent acceleration voltage value pattern 18j in the induced voltage arithmetic unit 22 with calculation results according to the selected charged particles and magnetic field excitation patterns.

[0179] Figure 10 shows a relationship between rapid cycling and the acceleration voltage. The operation scheme of the synchrotron 1 includes a rapid cycling scheme and a slow cycling scheme. The schemes include magnetic field excitation patterns 15 and 24 temporally changing in the process of accelerating the charged particle beam.

[0180] It has been described that the acceleration voltage 18a of a constant value can be used to accelerate arbitrary charged particles up to an arbitrary energy level in synchronization with the slow cycling magnetic field excitation pattern 15. However, according to the induction accelerating device 5 and the control method thereof of the present invention, the induced voltage for acceleration 18 may be synchronized with the slow cycling magnetic field excitation pattern 24.

[0181] The rapid cycling refers to acceleration by the magnetic field excitation pattern 24 with rapid cycling of one cycle 25 of about several ten milliseconds, one cycle starting from a time when the charged particles are injected 16a from the preinjector, and going through an acceleration time 16c and extraction 16b to the next injection 16a.

[0182] The first axis of ordinate B in Figure 10 represents magnetic field strength of the synchrotron 1 using the induction accelerating cell 6, and the second axis of ordinate v represents the voltage value of the induced voltage for acceleration 18. The first axis of abscissa t represents changes with time of the magnetic field excitation pattern 24, and the second axis of abscissa t (v) represents the generation time of the induced voltage for acceleration 18, and both refer to the time when the charged particle beam is injected 16a into the synchrotron 1 using the induction accelerating cell 6.

[0183] The rapid cycling magnetic field excitation pattern 24 has the amplitude of a sine curve, and the voltage value of the induced voltage for acceleration 18 synchronized with the magnetic field excitation pattern 24 is calculated by the above described formula (7) as in the method of the calculation from the slow cycling magnetic field excitation pattern 15.

[0184] The group of acceleration voltage values 18c calculated by the formula (7) is an ideal acceleration voltage value pattern 24a. The ideal acceleration voltage value pattern 24a is proportional to time differential of magnetic field changes in a certain time of the magnetic field excitation pattern 24, and thus changes of the acceleration voltage value 18c of a cosine curve is theoretically calculated.

[0185] Naturally, a reset voltage 18b equivalent to an ideal reset voltage value pattern 24c in a direction opposite to an ideal acceleration voltage value pattern 24a must be generated in a time period without the charged particle beam.

[0186] To apply the acceleration voltage 18a in synchronization with the magnetic field excitation pattern 24, a required acceleration voltage value 18c significantly increases or decreases with time as compared with the case of the slow cycling magnetic field excitation pattern 15.

[0187] However, according to the induction accelerating device 5 and the control method thereof of the present invention, the equivalent acceleration voltage value pattern 24b can be used to accurately control the acceleration voltage 18a at high speed in synchronization with the rapid cycling magnetic field excitation pattern 24 with complex changes of the acceleration voltage value 18c.

[0188] Thus, in all magnetic field excitation patterns, the induction accelerating device 5 and the control method thereof of the present invention can be used to accelerate arbitrary charged particles up to an arbitrary energy level.

[0189] Figure 11 shows an example (simulation) of the acceleration method of a charged particle beam according to the present invention. Acceleration behavior in acceleration of 10,000 charged particles (protons) up to an energy level of 40 to 500 MeV is shown. In the simulation, the following conditions were adopted.

[0190] A small-sized synchrotron (500 MeV booster synchrotron) for an injector of 12GeVPS was supposed and a peripheral length of a vacuum duct 2a thereof was used. For the digital signal processing device 12 that constitutes the induction accelerating device 5 according to the present invention, it was supposed that the variable delay time 14 was preset and the induced voltage 8 was supplied at an instant of passage of the bunch 3 through the induction accelerating cell 6.

[0191] The induced voltage arithmetic unit 22 previously stored the generation pattern (intermittent application) of the induced voltage 8, and a method of stopping the positive induced voltage 8a that functions as an unnecessary induced voltage for acceleration 18 was used so as to reduce deviation between "ideal energy of the charged particle beam determined from the magnetic field excitation pattern" and "energy of the charged particle beam in intermittent acceleration by the induced voltage".

[0192] Charging time periods 8c and 8d of the induced voltage 8 were 52 nsec, voltage amplitudes of the negative induced voltage 8b and the positive induced voltage 8a were 12 kV, and a time duration between generations 8e of the negative induced voltage 8b and the positive induced voltage 8a were fixed at 15 nsec.

[0193] The rectangular pulse shape of the induced voltage 8 was the same during acceleration without being changed

with time. From a restriction on an operation frequency of the switching power supply 5b (being 1 MHz or less), after the pair of negative induced voltage 8b and positive induced voltage 8a were generated, at least a 1 μ sec rest was necessary before the next pair of negative induced voltage 8b and positive induced voltage 8a were generated.

[0194] For the magnetic field excitation pattern, the linear excitation area 15b of the slow cycling magnetic field excitation pattern 15 that requires a constant acceleration voltage value 18c of 0.5 kV/turn was supposed in the 500 MeV booster synchrotron. At this time, the revolution frequency of the charged particle is 2 to 6 MHz, which is higher than the operation frequency of 1 MHz of the switching power supply 5b, and sharply changes.

[0195] The axis of abscissa Δt (nsec) in Figures 11(A) to (H) represents a deviation (time) of charged particles from design particles when the design particles are indicated by 0. The unit of time is nanosecond. Thus, Figures 11(A) to (H) show degrees of variations of the bunch 3 with respect to the design particles during acceleration.

[0196] The first axis of ordinate V (kV) represents the voltage value of the induced voltage 8. The second axis of ordinate $\Delta p/p$ (%) represents a momentum deviation, which corresponds to a deviation of energy of the charged particles. Figure 11(A) to (H) show part of turns from the 0th turn (Figure 11(A)) immediately after the injection 16a to the 600,000th turn (Figure 11(H)). The number of turns is indicated under each axis of abscissa Δt (nsec).

[0197] Figure 11(A) shows a state where the charged particles accelerated up to 40 MeV by the preinjector are injected 16a into the vacuum duct 2a, circulate along the design orbit 2, and form the bunch 3.

[0198] Figure 11(B) shows a state of the bunch 3 in the 1st turn. The induced voltage 8 is first applied to the bunch 3 circulating along the design orbit 2, and the negative induced voltage 8b is applied to the bunch head 3d and the positive induced voltage 8a is applied to the bunch tail 3e. Thus, it can be seen that the negative and positive induced voltages 8b and 8a function as the negative and positive barrier voltages 17a and 17b for confinement of the bunch 3.

[0199] Figure 11(C) shows a state of the bunch 3 in the 3rd turn. Timing for applying the positive induced voltage 8f and the negative induced voltage 8g is shown by the dotted lines, but the application thereof is stopped. The 3rd turn is the generation timing of the set induced voltage 8 described above, but the generation of the induced voltage 8 is stopped because the energy level of the charged particle beam is excessive with respect to the required acceleration voltage value 18i calculated from the magnetic field excitation pattern 24. Stopping the application of the positive and negative induced voltages 8a and 8b is actually determined by the induced voltage arithmetic unit 22 that constitutes the digital signal processing device 12.

[0200] Figure 11(D) shows a state of the bunch 3 in the 11th turn. Neither of the positive and negative induced voltages 8a and 8b are not applied. Even if the positive and negative induced voltages 8a and 8b that function as the barrier voltages 17 are not applied, a time period without the application of the positive and negative induced voltages 8a and 8b is within an acceptable range, and thus the bunch 3 is confined without diffusion. Also, even if the positive induced voltage 8a that functions as the acceleration voltage 18a is not applied, a time period without the application of the positive induced voltage 8a is within an acceptable range, and thus the bunch 3 is synchronized with the magnetic field excitation pattern 24. Thus, it can be seen that the charged particle beam can be accelerated by intermittently applying the induced voltage 8.

[0201] Figure 11(E) shows a state of the bunch 3 in the 12th turn. Herein, the positive induced voltage 8a is applied to the entire bunch mainly including the bunch center 3c, and thus functions as the acceleration voltage 18a. Thus, the negative induced voltage 8b functions as the reset voltage 18b.

[0202] Figure 11(F) shows a state of the bunch 3 in the 500th turn. The application of the positive induced voltage 8f and the negative induced voltage 8g shown by the dotted lines is stopped. The 500th turn is generation timing of the positive and negative induced voltages 8a and 8b, but the application is stopped as in Figure 11(C). The bunch 3 that is vertically long in Figure 11(A) is deformed to be horizontally long in Figure 11(F), and thus the synchrotron oscillation 3i can be confirmed by the intermittent application of the induced voltage 8 in the process. The deformation is mainly caused by adiabatic damping, but influenced by slight leakage from the confinement area of the charged particles.

[0203] Figure 11(G) shows a state of the bunch 3 in the 500,000th turn, and Figure 11(H) shows a state of the bunch 3 in the 600,000th turn. In both the drawings, it can be seen that the bunch 3 with a high density on the orbit close to the design particles is accelerated.

[0204] The acceleration method of a charged particle beam according to the present invention for intermittently applying the induced voltage 8 to the bunch 3 also allows the confinement of the bunch 3, the acceleration of the bunch 3 in synchronization with the magnetic field excitation pattern 24, the control of the synchrotron oscillation frequency, and the control of the beam orbit, thereby allowing the charged particle beam to be accelerated up to an arbitrary energy level.

[0205] The beam orbit control refers to controlling the generation timing of the induced voltage 8 to maintain the charged particle beam on the design orbit 2.

[0206] The synchrotron 1 maintains the bunch 3 on the design orbit 2 with the magnetic field strength by the bending magnet 4 that constitutes the synchrotron 1. The orbit of the charged particle beam is the design orbit 2 that is placed around a point outside or inside the center of the vacuum duct 2a, which is determined by arrangement of the bending magnet 4 that constitutes the synchrotron 1, rather than placed around the center of the vacuum duct 2a.

[0207] Without the magnetic field strength by the bending magnet 4, the bunch 3 would collide with a wall surface of

the vacuum duct 2a with a centrifugal force of the charged particle beam and be lost. The magnetic field strength changes with the acceleration time 16c. The changes are the magnetic field excitation patterns 15 and 24.

[0208] Once the kind of charged particles to be accelerated, an acceleration energy level, and a peripheral length of the synchrotron 1 are determined, a revolution frequency band width of the charged particle beam is uniquely determined.

Thus, like the rf acceleration voltage, the induced voltage 8 that functions as the induced voltage for acceleration 18 must be applied to the charged particle beam for acceleration in the advancing axis direction 3a in synchronization with the magnetic field excitation patterns 15 and 24.

[0209] However, the voltage value of the induced voltage 8 applied to the bunch 3 is not constant but slightly increases or decreases. This is because of various factors such as deviation of the charging voltage of the bank capacitor 5f from an ideal value.

[0210] When an acceleration voltage value 18c lower than the ideal acceleration voltage value 18c is actually applied because of the synchronization with the magnetic field excitation patterns 15 and 24, the bunch 3 is displaced inward from the design orbit 2. On the other hand, when an acceleration voltage value 18c higher than the ideal acceleration voltage value 18c is actually applied, the charged particle beam is displaced outward from the design orbit 2.

[0211] It is supposed that a method of correcting the charged particle beam along the design orbit 2 includes changing the level of the acceleration voltage value 18c. However, the induction accelerating device 5 that generates the acceleration voltage value 18c must include a large bank capacitor 5f (capacitance) in a high pressure charging unit of the switching power supply 5b that determines the amplitude of the pulse voltage 6f for obtaining stable output electric power of some ten kW required by the induction accelerating cell 6.

[0212] A charging pressure of the bank capacitor 5f is intended for stable output of the pulse voltage 6f, and cannot change at high speed. Thus, the amplitude of the pulse voltage 6f cannot be actually controlled at high speed.

[0213] Thus, when the DC power supply 5c and the bank capacitor 5f to use are determined, the output voltage is uniquely determined, and thus the voltage value cannot be significantly changed in a short time period. Thus, in the method of changing the amplitude of the pulse voltage 6f, the induced voltage 8 cannot be synchronized with the magnetic field excitation patterns 15 and 24.

[0214] Without eliminating the above described deviation of the voltage value of the induced voltage 8, once the charged particle beam receives the acceleration voltage value 18c higher than the required acceleration voltage value 18c in the synchrotron 1 using the induction accelerating cell 6, the charged particle beam is displaced outward from the design orbit 2 by the centrifugal force of the charged particle beam and cannot be accelerated.

[0215] Thus, to solve the above described problem, the pulse density 19 is corrected in real time in the unit of control 15c, and the positive induced voltage 8a that functions as the acceleration voltage 18a is applied to the charged particle beam on the basis of the corrected pulse density 19, thereby correcting the displacement of the orbit of the charged particle beam.

[0216] Specifically, in the slow cycling synchrotron 1, an orbit control method of the charged particle beam using the digital signal processing device in Figure 9 will be described. For the variable delay time 14, a required variable delay time pattern 14b is previously calculated and stored in the variable delay time calculator 20.

[0217] The variable delay time calculator 20 generates the variable delay time signal 20a corresponding to the variable delay time 14 on the basis of the required variable delay time pattern 14b, and the variable delay time generator 21 receives the passage signal 9a of the bunch 3 from the bunch monitor 9 on the design orbit 2 along which the charged particle beam circulates and the variable delay time signal 20a from the variable delay time calculator 20 to generate the pulse 21a corresponding to the variable delay time 14.

[0218] The induced voltage arithmetic unit 22 that stores the equivalent acceleration voltage value pattern 18j corresponding to the ideal acceleration voltage value pattern 18f calculated on the basis of the magnetic field excitation pattern 15, and generates the pulse 22a for controlling on/off the induced voltage 8 that functions as the induced voltage for acceleration 18 receives the pulse 21a corresponding to the variable delay time 14 from the variable delay time generator 21 and a position signal 11a from the position monitor 11 that detects the displacement of the charged particle beam on the design orbit 2 from the design orbit 2 to stop application of the excessive induced voltage for acceleration 18 from the pulse density 19 in the unit of control 15c.

[0219] The gate master signal output device 23 receives the pulse 22a that is on/off information of the induced voltage 8 calculated by the induced voltage arithmetic unit 22 to generate the gate master signal 12a that is a pulse suitable for the pattern generator 13.

[0220] The gate master signal 12a thus calculated by the digital signal processing device 12 is converted into the gate signal pattern 13a that is the combination of on and off of the current path of the switching power supply 5b by the pattern generator 13. In this manner, on/off of the induced voltage 8 is controlled to stop application of the excessive induced voltage 8.

[0221] To stop the excessive induced voltage 8, the bunch monitor 9 for checking the passage of the bunch 3, the speed monitor 10 for measuring the acceleration speed of the bunch 3 in real time, and the position monitor 11 for detecting the degree of displacement of the charged particle beam horizontally inward or outward from the design orbit 2.

[0222] The bending magnet 4 has a structure in which a conductor is wound around an iron core or an air core like a coil, and a current is passed through the conductor to generate magnetic field strength perpendicular to the advancing axis of the charged particle beam. Since the magnetic field strength of the bending magnet 4 is proportional to the current passing through the conductor, the proportional coefficient is previously calculated, and a current rate is measured and converted to calculate the magnetic field strength.

[0223] The speed monitor 10 generates a voltage value, a current value, or a digital value according to a revolution speed of the bunch 3. The speed monitor 10 includes one having an analogue structure in which voltage pulses or current pulses generated in the passage of the charged particle beam are accumulated in a capacitor and converted into a voltage value like the bunch monitor 9, and one having a digital structure in which the number of the voltage pulses is counted by a digital circuit.

[0224] The position monitor 11 outputs a voltage value proportional to the displacement of the bunch 3 from the design orbit 2. The position monitor 11 includes, for example, two conductors each having a slit slanting in the advancing axis direction 3a, and charges are induced in a conductor surface with the passage of the bunch 3. Since the amount of induced charges depends on the position between the bunch 3 and the conductor, the amount of charges induced in the two conductors differs depending on the position of the bunch 3, and thus there is a difference between the voltage values induced in the two conductors.

[0225] For example, when the bunch 3 passes through the center of the position monitor 11, equal voltages are induced, and an output voltage value of a difference between the voltages generated in the two conductors is 0. When the bunch 3 passes through outside the design orbit 2, a positive voltage value proportional to the displacement from the center is output, and when the bunch 3 passes through inside the design orbit 2, a negative voltage value proportional to the displacement from the center is output.

[0226] Thus, the bending magnet 4, the bunch monitor 9, the speed monitor 10, and the position monitor 11 used in acceleration of the rf synchrotron can be used.

[0227] Signals used for controlling the generation timing of the induced voltage for acceleration 18 includes a cycle signal 4a output from the bending magnet 4 (via the control device of the accelerator) at the instant of injection of the charged particle beam from the preinjector, the beam deflection magnetic field strength signal 4b that is the magnetic field excitation pattern in real time, the passage signal 9a from the bunch monitor 9 that is information on the passage of the charged particle beam through the bunch monitor 9, a speed signal 10a indicating a revolution speed of the bunch 3, and a position signal 11a from the position monitor 11 that is information on the displacement of the circulating charged particle beam from the design orbit 2.

[0228] The variable delay time 14 can be previously calculated and provided as the required variable delay time pattern 14b when the kind of the charged particles and the magnetic field excitation pattern are previously determined.

[0229] However, when the variable delay time 14 is previously calculated, the orbit of the charged particle beam cannot be corrected if the charged particle beam is displaced inward or outward from the design orbit 2. Thus, when the variable delay time 14 is previously calculated, the induced voltage arithmetic unit 22 corrects the positive induced voltage 8a that functions as the induced voltage for acceleration 18.

[0230] If the speed monitor 10 for measuring the revolution speed of the charged particle beam is used, and the speed signal 10a that is the revolution speed of the charged particle beam is input to the variable delay time calculator 20 in real time, the variable delay time 14 can be calculated in real time by the formulas (1) and (2) without providing information on the kind of the charged particles.

[0231] The variable delay time 14 is calculated in real time to allow the orbit of the charged particle beam to be corrected by correcting the generation timing of the induced voltage 8 if the applied acceleration voltage value 18c is changed from a predetermined set value by the DC power supply 5c, the bank capacitor 5f, or the like that constitute the induction accelerating device 5, and some disturbance causes a sudden change in the revolution speed of the bunch 3.

[0232] To the variable delay time calculator 20, the cycle signal 4a is input from the bending magnet 4 (via the control device of the accelerator). The cycle signal 4a is a pulse voltage generated from the bending magnet 4 (via the control device of the accelerator) when the charged particle beam is injected into the synchrotron 1, and information on the start of acceleration. Generally, the synchrotron 1 repeats the injection 16a, the acceleration, and the extraction 16b of the charged particle beam multiple times.

[0233] Thus, when the variable delay time 14 is previously started, the variable delay time calculator 20 receives the cycle signal 4a indicating the start of acceleration, and outputs the variable delay time signal 20a to the variable delay time generator 21 on the basis of the previously calculated variable delay time 14.

[0234] As described above, to correct the orbit of the charged particle beam displaced from the design orbit 2 because of the nonconstant voltage value of the induced voltage 8 and sudden trouble during acceleration, it is necessary to stop the generation of the induced voltage 8, that is, to change the pulse density 19.

[0235] For the induced voltage arithmetic unit 22 to correct the orbit of the charged particle beam, information on how far the orbit of the charged particle beam is displaced outward from the design orbit 2 by how much acceleration voltage value 18c is supplied to the charged particle beam needs to be previously provided to the acceleration voltage arithmetic

unit 16 as basic data for correction.

[0236] Next, the induced voltage arithmetic unit 22 receives the amount of displacement of the charged particle beam from the design orbit 2 as the position signal 11a from the position monitor 11 on the design orbit 2 at a time point during the acceleration, and performs calculation for correcting the orbit of the charged particle beam in real time for each turn of the bunch 3.

[0237] An acceleration voltage per one turn required for correcting the orbit of the charged particle beam at the number of turns n in the unit of control is approximately calculated by the following formula (9):

$$V = C_0 \times (B' \times \rho + B \times \rho') \dots \text{Formula (9)}$$

where p is a present orbit radius, p' is time differential thereof, B is magnetic field strength, B' is time differential thereof, and C_0 is the entire length of the synchrotron.

[0238] The value V is an average acceleration voltage value applied by the induction accelerating cell 6 in the unit of control 15c. Naturally, the right side of the formula (9) can be expanded to an arbitrary formula expressed by a numerical calculation formula obtained from modern control theory or the like.

$$V = (m/n) V_{acc} (m < n) \dots \text{Formula (10)}$$

where V_{acc} is an ideal acceleration voltage value calculated by the formula (7).

[0239] The values p' and B' are calculated by the following formulas (11) and (12):

$$p' = \Delta p / (\Sigma t) \dots \text{Formula (11)}$$

$$B' = \Delta B / (\Sigma t) \dots \text{Formula (12)}$$

where t is a revolution time of the bunch 3 per one turn, Δp an orbit radius in the unit of control, ΔB is a change in magnetic field strength in the unit of control 15c, and Σt is a total time of t added for the number of turns n . When the induced voltage 8 is controlled in real time, p' and B' are calculated by the induced voltage arithmetic unit 22.

[0240] The revolution time t of the bunch 3 per one turn is calculated by the following formula (13):

$$t = C_0 / v \dots \text{Formula (13)}$$

where v is the revolution speed obtained from the speed monitor 10 or the like and C_0 is the entire length of the synchrotron. The value t is different for each turn of the bunch 3.

[0241] On the basis of the calculation results of the acceleration voltage value obtained from these processes, a required induced voltage 8 is applied, or application of the positive induced voltage 8a that functions as the induced voltage for acceleration 18 corresponding to the excessive acceleration voltage value is stopped. Stopping the application of the positive induced voltage 8a means that generation to be performed next of the positive induced voltage 8a that functions as the acceleration voltage 18a is not performed.

[0242] The orbit of the charged particle beam is displaced outward from the design orbit 2 because the acceleration voltage value 18c applied to the charged particle beam is more excessive than the acceleration voltage value 18c required at the instant to prevent synchronization with the magnetic field excitation pattern of the bending magnet 4.

[0243] Thus, the excessive acceleration voltage value is calculated from the equivalent acceleration voltage value pattern 18j calculated previously or in real time from the magnetic field excitation pattern 15, and the displacement of the orbit obtained from the position signal 11a, and the pulse density is corrected by subtracting the excessive acceleration voltage value from the previously provided equivalent acceleration voltage value pattern 18j.

[0244] Correcting the pulse density 19 means stopping the application of the positive induced voltage 8a that functions as the acceleration voltage 18a corresponding to the excess of the acceleration voltage value in the acceleration voltage

value 18c previously provided and required at the instant and the pulse density 19 in the unit of control 15c.

[0245] Besides the previously provided equivalent acceleration voltage value pattern 18j, for example, when the charged particle beam is even slightly displaced outward from the design orbit 2, it is allowed that pulse densities 19 for correcting the orbit of the charged particle beam for "significant correction" or "gentle correction" are previously provided, and a required pulse density 19 is selected to control the orbit of the charged particle beam.

[0246] Alternatively, the orbit of the charged particle beam may be maintained on the design orbit 2 by replacing the pulse density 19 in the unit of control 15c in a certain time of the equivalent acceleration voltage value pattern 18j with another pulse density 19 stored in the induced voltage arithmetic unit 22.

[0247] When on/off of the variable delay time 14 and the induced voltage 8 is controlled in real time, the induced voltage 8 is controlled for each turn of the bunch 3 to position the orbit of the charged particle beam on the design orbit 2.

[0248] The above described control method is used to allow appropriate orbit control in changes of the orbit of the charged particle beam that differs depending on the size of the accelerator.

[0249] The magnetic field excitation pattern 15, the equivalent acceleration voltage value pattern 18j, the basic data for correction, and the pulse density 19 for correction are replaceable data, and can be changed according to the kind of selected charged particles or the magnetic field excitation pattern.

[0250] By simply replacing the data, the induction accelerating device 5 according to the present invention can be used for accelerating arbitrary charged particles up to an arbitrary energy level.

[0251] Controlling the orbit of the charged particle beam requires calculation of the acceleration voltage value 18c required in a certain time for each turn of the bunch 3 in real time. When the acceleration voltage value 18c required in a certain time is calculated in real time, it is only necessary to receive the magnetic field strength at that time as the beam deflection magnetic field strength signal 4b from the bending magnet 4 (via the control device of the accelerator) that constitutes the synchrotron 1 using the induction accelerating cell 6, and calculate the acceleration voltage value 18c by a calculation formula as in the case of previous calculation.

[0252] The induced voltage signal 5e that is the voltage value of the induced voltage 8 obtained from the induced voltage monitor 5d that is the ammeter in Figure 9 may be fed back to the induced voltage arithmetic unit 22 of the digital signal processing device 12 to calculate the equivalent acceleration voltage value pattern 18j corresponding to the ideal acceleration voltage value pattern 18f.

[0253] The position monitor 11 and the induced voltage monitor 5d are concurrently used to check the displacement of the orbit of the charged particle beam more accurately, thereby allowing more accurate control of the orbit of the charged particle beam.

[0254] Thus, the induced voltage arithmetic unit 22 has the function of measuring the acceleration voltage value required for correcting the orbit of the charged particle beam in real time, and intermittently outputting the pulse 22a for correcting the pulse density 19 based on the equivalent acceleration voltage value pattern 18j previously provided to the induced voltage arithmetic unit 22 rather than simply outputting the acceleration voltage 18a for each turn of the bunch 3 using the passage signal 9a sent from the bunch monitor 9.

[0255] Thus, the induction accelerating device 5 according to the present invention is used to control the variable delay time 14 and the pulse density 19 of the induced voltage 8 that functions as the induced voltage for acceleration 18, thereby allowing the charged particle beam to be maintained on the design orbit 2 without being displaced therefrom for all magnetic field excitation patterns even by the induction accelerating cell 6 that can apply only the acceleration voltage 18a of a substantially constant voltage value (V_0) to the design orbit 2.

[0256] The generation timing of the induced voltage 8 is controlled in real time by the induction accelerating device 5 according to the present invention to correct the pulse density in real time, and correct the displacement of the orbit of the charged particle beam in synchronization with all synchrotron operation schemes, that is, all magnetic field excitation patterns so that the charged particle beam is positioned on the original design orbit 2.

[0257] Also, the charged particle beam may be circulated along an arbitrary orbit inside or outside the design orbit 2.

[0258] Figure 12 shows part of the generation pattern of the induced voltage in acceleration simulation in Figure 11. The axis of abscissa (T) represents the number of turns of the bunch 3 up to 100 turns, and on the axis of ordinate, acc. represents generation of the induced voltage for acceleration 18, con. represent generation of the barrier voltage, and off represents non-generation of the induced voltage 8.

[0259] The induced voltage for acceleration 18k shown by the dotted lines has been programmed in the induced voltage arithmetic unit 22 as timing generated in the induced voltage arithmetic unit 22, but is prevented from being generated because the energy level of the charged particle beam is more excessive than the equivalent acceleration voltage value pattern 24b calculated from the magnetic field excitation pattern 24.

[0260] If the magnetic field excitation pattern is provided, energy of the design particles at certain timing $t = t_0$ is provided. Thus, it is determined whether the energy level is excessive by comparing the energy level with the sum of the acceleration voltage values 18c intermittently supplied from the start of the acceleration to the timing $t = t_0$ multiplied by the charge e .

[0261] As is seen from the generation pattern of the induced voltage 8 in Figure 12, among 100 turns of the bunch 3,

the induced voltage 8 as the induced voltage for acceleration 18 is applied for 6 turns, and the induced voltage 8 as the barrier voltage 17 is applied for 22 turns. Thus, it can be seen that the charged particle beam can be accelerated by intermittently applying induced voltages 8 having the same pulse shape and multiple functions from a set of induction accelerating devices 5 rather than applying the induced voltages 8 for each turn of the bunch 3.

[0262] It can be also seen that since there are turns of the bunch 3 without application of the induced voltage 8, the induced voltage 8 that functions as the barrier voltage 17 for controlling the synchrotron oscillation frequency and the induced voltage 8 that functions as the induced voltage for acceleration 18 for controlling the beam orbit can be applied to the bunch 3 at the timing.

[0263] Figure 13 shows a method (simulation) of forming a super-bunch by the acceleration method of a charged particle beam according to the present invention.

[0264] In order from Figures 13(A) to (I), three bunches 3, 3j and 3l are connected to form a super-bunch 3m. In Figures 13(A) to (F), turn represents the number of turns of the bunch with a turn at which the induced voltage 8 is first applied to the bunch 3 being the 0th turn, and in Figures 13(F) to (H), turn represents the number of turns of the bunch 3 with a turn at which the induced voltage 8 is first applied to a bunch 3k being the 0th turn, in the case where a third bunch 3l is connected to the bunch 3k that is a connection of the two bunches 3 and 3j.

[0265] The axis of abscissa time [nsec] represents a generation time of the induced voltage 8 with a time when the negative induced voltage 8b that functions as the negative barrier voltage 17a applied to the bunch 3 injected 16a into the vacuum duct 2a is first applied being zero. The axis of abscissa time [nsec] also represents a position of a phase space of the charged particles.

[0266] The first axis of ordinate $\Delta p/p$ [%] represents a momentum deviation, which corresponds to displacement of energy of the charged particles. The second axis of ordinate Vstep [V] represents the voltage value of the induced voltage 8.

[0267] The simulation condition is as follows: the pulse amplitude is 5.8 kV, the charging time periods 8c and 8d are 250 nsec, a time duration between generations 8e of the positive and negative induced voltages 8a and 8b is 80 nsec. For the bunches 3, 3j and 3l injected 16a in the simulation, $\Delta p/p$ (%) is 0.1%. Generation times of the positive and negative induced voltages 8a and 8b for confinement of the bunch 3 to be connected are moved toward the bunch to be connected by 10 nsec per 100 turns.

[0268] Figure 13(A) shows a state where the bunch 3 is confined by the positive induced voltage 8a and the negative induced voltage 8b among the bunches 3 and 3j injected 16a into the vacuum duct 2a. Specifically, the induced voltage 8 applied here functions as the barrier voltage 17.

[0269] Figure 13(B) shows a state of the 310th turn. The bunch 3j is confined by the positive induced voltage 8a and the negative induced voltage 8b. Specifically, the induced voltage 8 applied here functions as the barrier voltage 17 to the bunch 3j.

[0270] The bunches 3 and 3j receive the barrier voltage 17, and thus the occurrence of the synchrotron oscillation 3i can be found. Since only the negative induced voltage functions as the barrier voltage 17 to the bunch 3, the synchrotron oscillation 3i occurs on the right side of the bunch 3, and the charged particles are slightly diffused on the left side of the bunch 3.

[0271] Figure 13(C) shows a state of the 1302nd turn. The bunch 3 and the bunch 3j are brought close to each other and partly integrated. The positive and negative induced voltages 8a and 8b here function as the barrier voltages 17 to the bunch 3. The positive induced voltage 8a partly influences (accelerates) the bunch head 3d of the bunch 3j, but the charged particles that constitute the bunch 3j do not extremely disappear.

[0272] Figures 13(D) and (E) show states of the 3130th turn and the 5947th turn. In Figures 13(D) and (E), it can be seen that the bunch 3j is gradually brought close and connected to the bunch 3 to form the bunch 3k. Herein, positive and negative induced voltages 8h and 8i that are used neither for the barrier voltage 17, for the induced voltage for acceleration 18, nor for control of the synchrotron oscillation frequency, that is, that have no function are applied.

[0273] In Figure 13(D), the positive induced voltage 8a functions as the positive barrier voltage 17b to the bunch 3k. However, the negative induced voltage 8i is applied to a bunch center 3c of the bunch 3k newly formed by the connection of the two bunches 3 and 3j, as the induced voltage 8 in a direction opposite to the advancing axis direction 3a.

[0274] Thus, the negative induced voltage 8i is the induced voltage 8 having no function and unnecessary. However, unless the positive and negative induced voltages 8a and 8b are alternately applied, electrical saturation of the magnetic material 6c occurs as described above to prevent application of the induced voltage 8.

[0275] Thus, such unnecessary positive and negative induced voltages 8a and 8b are applied in pairs at the close numbers of turns and cancel each other out, thereby reducing influence of the unnecessary positive and negative induced voltages 8a and 8b to the charged particle beam. Also in Figure 13(E), the negative induced voltage 8i is unnecessary.

[0276] Comparing the time duration between generations 8e of the positive and negative induced voltages 8a and 8b in Figures 13(B) and (D), (D) shows the state of the turn of the bunch 3 about 2800 turns after (B), and it can be seen that the generation is about 280 nsec earlier (about 2800 turns/100 turns \times 10 nsec = about 280 nsec).

[0277] Figure 13(F) shows a first stage (the 0th turn) in the case where another bunch 3l is connected to the bunch

3k newly formed by the connection of the two bunches 3 and 3j. The time duration between generations 8e of the positive and negative induced voltages 8a and 8b is returned to 80 nsec as in Figure 13(A).

[0278] Herein, the negative induced voltage 8b applied to the bunch 3k functions as the negative barrier voltage 17a. The positive induced voltage 8a is applied to the bunch center 3c of the bunch 3k as the positive induced voltage 8h having no function. Similarly, the negative induced voltage 8i in Figure 13(G) showing the 165th turn is also unnecessary. The positive and negative induced voltages 8h and 8i having no function are applied at the close number of turns, and cancel each other out in pairs.

[0279] Figure 13(H) shows a state of the 330th turn, in which the positive and negative induced voltages 8a and 8b are applied to the third bunch 3i newly connected. The induced voltage 8 has the function of confinement of the bunch 3i and thus functions as the barrier voltage 17. Also herein, the synchrotron oscillation 3i can be seen.

[0280] Figure 13(I) shows particle density distribution 3n of the formed super-bunch 3m. The axis of abscissa time [nsec] represents a time width in which charged particles exist with the generation time of the negative induced voltage 8b applied to the bunch head 3d by the induction accelerating cell 6 being zero. Also herein, the synchrotron oscillation 3i can be seen.

[0281] The first axis of ordinate $\Delta p/p$ [%] represents momentum deviation, which corresponds to displacement of energy of the charged particles. The second axis of ordinate density represents particle density distribution 3n of the charged particles, and the unit thereof is relative ratio.

[0282] The negative induced voltage 8b having the same function as the negative barrier voltage 17a is applied to the bunch head 3d, and the positive induced voltage 8a having the same function as the positive barrier voltage 17a is applied to the bunch tail 3e, thereby confining the super-bunch 3m. This allows confinement of the super-bunch 3m and control of the synchrotron oscillation frequency.

[0283] In this manner, the set of induction accelerating device 5 according to the present invention can be used to intermittently supply the induced voltage 8 to connect the multiple bunches 3 to form the super-bunch 3m. The time duration between generations 8e of the positive and negative induced voltages 8a and 8b is adjusted to the length of the super-bunch 3m to allow confinement, and the charging time period 18e for applying the voltage to the entire length of super-bunch 3m is ensured to accelerate the super-bunch 3m up to the an arbitrary energy level.

[0284] A device and a method for applying the acceleration voltage 18a to the entire super-bunch 3m will be described in detail with reference to Figure 14.

[0285] Figure 14 shows an example of changing an induced voltage value using multiple induction accelerating cells. Generally, a charging time period and a voltage value are required such that the negative and positive barrier voltages 17a and 17b are relatively high in a short charging time period, the acceleration voltage 18a is relatively low in a long charging time period, and the reset voltage 18b is equal in energy to the acceleration voltage 18a.

[0286] The above described requirement can be easily satisfied by using the multiple induction accelerating cells 6. Thus, an operation pattern in use of triple induction accelerating cells 6 will be described. This method allows an increase in flexibility of selection of charged particles and attainable energy levels.

[0287] Figure 14(A) shows the level of the barrier voltage 17 supplied by the triple induction accelerating cells 6 and the charging time period. The axis of abscissa t represents the charging time period of the barrier voltage 17 and the axis of ordinate $V(t)$ represents the voltage value of the barrier voltage 17.

[0288] In Figures 14(A), (1), (2) and (3) denote barrier voltages 17 applied from the first induction accelerating cell 6, the second induction accelerating cell 6, and the third induction accelerating cell 6, respectively. (4) denotes the total negative and positive barrier voltage values 17e and 17f applied to the bunch 3 by the triple induction accelerating cells 6.

[0289] A negative barrier voltage 17a is first applied to the bunch head 3d of the bunch 3 that has reached the triple induction accelerating cells 6 at the same number of turns in order from (1) to (3). At this time, the bunch 3 circulates at high speed, and it is only necessary that the negative barrier voltages 17a from (1) to (3) are applied substantially at the same time.

[0290] Similarly, the positive barrier voltages 17b are applied to the bunch tail 3e. Thus, the voltage values equal to the total positive barrier voltage values 17e and 17f in (4) are applied to the bunch 3 at the bunch head 3d and the bunch tail 3e.

[0291] In this manner, the induction accelerating cells 6 are combined to shift generation timing of the induced voltages of the induction accelerating cells 6 at the same number of turns, thereby allowing high barrier voltage values 17e and 17f to be obtained even if the negative and positive barrier voltage values 17c and 17d applied by each induction accelerating cell 6 are low. Specifically, the voltage values of effectively required barrier voltages 17 (the positive and negative induced voltages 8a and 8b that function as the barrier voltages 17) can be easily changed. This requires the same number of induction accelerating devices 5 as that of the induction accelerating cells 6.

[0292] In the case where the barrier voltages are intermittently supplied at different turns rather than at the same turn, the barrier voltage value becomes an average value using the number of turns, and becomes lower than the negative and positive barrier voltage values 17c and 17d applied by the induction accelerating cell 6. In this case, the set of induction accelerating device 5 can easily change the voltage value of the effectively required barrier voltage 17. This

is cost-effective because the multiple induction accelerating cells 6 are not required.

[0293] Figure 14(B) represents the level of the induced voltage for acceleration 18 supplied by the triple induction accelerating cells 6 and the charging time period 18e. The axis of abscissa t represents the charging time period 18e of the induced voltage for acceleration 18, and the axis of ordinate $V(t)$ represents the voltage value of the induced voltage for acceleration 18.

[0294] In Figure 14(B), (1), (2) and (3) represent induced voltages for acceleration 18 applied from the first induction accelerating cell 6, the second induction accelerating cell 6, and the third induction accelerating cell 6, respectively. (4) represents the total charging time period 18m of the acceleration voltage 18a applied to the bunch 3 by the triple induction accelerating cells 6 and the total reset voltage value 18n.

[0295] An acceleration voltage 18a at a certain acceleration voltage value 18c is first applied to the bunch 3 that has reached the triple induction accelerating cells 6 at the same number of turns in order from (1) to (3). At this time, the charging time periods are shifted from (1) to (3), and thus the acceleration voltages 18a can be applied to the bunch 3.

[0296] This ensures a charging time period equal to the total charging time period 18m in (4) for the entire bunch 3.

[0297] A reset voltage 18b is applied for avoiding magnetic saturation of the triple induction accelerating cells 6 in a time period when no bunch 3 exists in the induction accelerating cells 6. The total reset voltage value 18n is effectively three times higher than the reset voltage 18b, but a voltage applied to each induction accelerating cell 6 is substantially equal to or lower than the reset voltage 18b, and there is lower risk of breakage due to discharge than in the case where one induction accelerating cell 6 supplies the acceleration voltage 18a and the reset voltage value 18n.

[0298] In the case where the acceleration voltages 18a are intermittently supplied at different turns rather than at the same turn, like the barrier voltage 17, the charging time period of the effectively required acceleration voltage 18a (positive induced voltage 8a that functions as the acceleration voltage 18a) can be ensured by the set of induction accelerating device 5 using the multiple induction accelerating cells 6. This is cost-effective because the multiple induction accelerating cells are not required. The same applies to the reset voltage 18b (negative induced voltage 8b that functions as the reset voltage 18b).

[0299] In theory, the time period other than the time period for the application of the reset voltage 18b can be used as the time period for the application of the acceleration voltage 18a, thereby allowing an arbitrary charged particle beam to be accelerated as the super-bunch 3m.

[0300] In this manner, even if one induction accelerating cell 6 can apply the acceleration voltage 18a only in a short charging time period 18e, the induction accelerating cells are combined to ensure a long charging time period 18m. Specifically, the two functions of confinement and acceleration can be sufficiently exerted even by the induction accelerating cell that can only generate a low induced voltage. This can reduce production costs of an accelerator using the induction accelerating cell 6.

[0301] Figure 15 is a general block diagram of an accelerator including an induction accelerating device according to the present invention. In the accelerator 26 according to the present invention, devices used in a conventional complex of rf synchrotron devices may be used as devices other than an induction accelerating device 5 for controlling acceleration of a bunch 3.

[0302] The accelerator 26 includes an injection device 29, an induction synchrotron 27, and an extraction device 33. The injection device 29 includes an ion source 30, a preinjector 31, an injector 32, and transport pipes 30a and 31a that connect the devices and are communication passages for a charged particle beam, upstream of the induction synchrotron 27.

[0303] As the ion source 30, an ECR ion source using an electronic cyclotron resonance heating mechanism, a laser driven ion source, or the like is used.

[0304] As the preinjector 31, a variable-voltage electrostatic accelerator or a linear induction accelerator is generally used. When the kind of charged particles to be used is determined, a small-sized cyclotron may be used.

[0305] As the injector 32, a device used in the complex of rf synchrotron is used. No particular device and method is required for the accelerator 26 of the present invention.

[0306] In the injection device 29 having the above described configuration, the charged particles generated by the ion source 30 are accelerated by the preinjector 31 up to a certain energy level and injected into the induction synchrotron 27 by the injector 32.

[0307] The induction synchrotron 27 includes an annular vacuum duct 2a having a design orbit 2 of the charged particle beam therein, a bending magnet 4 that is provided on a curved portion of the design orbit 2 and holds a circular orbit of the charged particle beam, a focusing electromagnet 28 that is provided on a linear portion of the design orbit 2 and prevents diffusion of the bunch 3, a bunch monitor 9 that is provided in the vacuum duct 2a and detects passage of the bunch 3, a position monitor 11 that is provided in the vacuum duct 2a and detects the center of gravity position of the bunch 3, and the induction accelerating device 5 that is connected to the vacuum duct 2a and controls generation timing of induced voltages 8 for confinement and acceleration of the bunch 3 in an advancing axis direction 3a.

[0308] The induction accelerating device 5 has a configuration shown in Figure 1, and a digital signal processing device 12 has a configuration shown in Figure 9. The induction accelerating device 5 controls the generation timing of

the induced voltage 8, confines and accelerates the charged particle beam, and moves the bunch 3. The confinement provides phase stability to the bunch 3 to control the synchrotron oscillation frequency of the bunch 3. Further, the acceleration voltage 18a can be applied to freely control a revolution orbit of the charged particle beam.

[0309] Since the bunch 3 can be moved, multiple bunches 3 can be connected to form and accelerate a super-bunch 3m.

[0310] The extraction device 33 includes a transport pipe 34a that connects to a facility 35a in which experimental devices 35b or the like using the charged particle beam accelerated up to the predetermined energy level by the induction synchrotron 27 are placed, and an extraction system 34 that extracts the charged particle beam to a beam utility line 35. The experimental devices 35b include medical facilities used for therapy.

[0311] As the extraction system 34, a kicker magnet for rapid extraction, or a device for slow extraction using betatron resonance or the like may be used, and the extraction system can be selected depending on the kinds and the ways of use of the charged particle beam.

[0312] With the above described configuration, the accelerator 26 of the present invention by itself can accelerate all charged particles up to an arbitrary energy level.

Industrial Applicability

[0313] The present invention has the above described configuration and can obtain the following advantages. First, one set of induction accelerating device 5 can control the generation timing of the positive induced voltage 8a and the negative induced voltage 8b, and apply the induced voltages 8 to the charged particle beam at arbitrary timing. Thus, the charged particle beam can be synchronized with the magnetic field excitation patterns 15 and 24 by the bending magnet 4, the charged particle beam can be sufficiently confined in the charging time period 18e of the acceleration voltage 18a, the synchrotron oscillation frequency can be controlled, further the beam orbit can be controlled, and arbitrary charged particle beams in all charged states that may be taken in principle can be accelerated up to an arbitrary energy level.

[0314] Second, the generation timing of the induced voltage 8 can be controlled to reduce the time duration between generations 8e of the induced voltages 8 that function as the barrier voltages 17 applied by the set of induction accelerating device 5 to form the super-bunch 3m.

[0315] Third, the set of induction accelerating device 5 controls the induced voltages 8 having multiple functions, thereby significantly increasing flexibility of acceleration control of the charged particle beam.

[0316] Fourth, the set of induction accelerating device 5 controls acceleration of the charged particle beam to reduce construction costs of the accelerator. Thus, arbitrary charged particle beams for medical use can be provided at low costs. The set of induction accelerating device 5 may be simply incorporated into the conventional rf synchrotron.

Claims

1. An induction accelerating device in a synchrotron, **characterized by** comprising:

an induction accelerating cell that applies an induced voltage;
a switching power supply that supplies a pulse voltage to said induction accelerating cell via a transmission line and drives said induction accelerating cell;
a DC power supply that supplies electric power to said switching power supply; and
an intelligent control device including a pattern generator that generates a gate signal pattern for controlling on/off said switching power supply, and a digital signal processing device that controls on/off a gate master signal that becomes the basis of said gate signal pattern.

2. The induction accelerating device according to claim 1, **characterized in that** said digital signal processing device includes:

a variable delay time calculator that stores a required variable delay time pattern corresponding to an ideal variable delay time pattern calculated on the basis of magnetic field excitation patterns, and generates a variable delay time signal on the basis of said required variable delay time pattern;
a variable delay time generator that receives a passage signal of a bunch from a bunch monitor placed on a design orbit along which a charged particle beam circulates and the variable delay time signal from said variable delay time calculator to generate a pulse corresponding to a variable delay time;
an induced voltage arithmetic unit that stores an equivalent acceleration voltage value pattern corresponding to an ideal acceleration voltage value pattern calculated on the basis of the magnetic field excitation patterns,

and receives the pulse corresponding to the variable delay time from said variable delay time generator to generate a pulse for controlling on/off the induced voltage; and
 a gate master signal output device that receives the pulse from said induced voltage arithmetic unit to generate the gate master signal that is a pulse suitable for the pattern generator, and outputs the gate master signal after
 5 a lapse of the variable delay time; and
 a gate signal output device, and
 said induction accelerating device controls generation timing of the induced voltage.

3. The induction accelerating device according to claim 2, **characterized in that** said variable delay time calculator calculates the variable delay time in real time on the basis of a beam deflection magnetic field strength signal indicating magnetic field strength of a bending magnet that constitutes the synchrotron, and a revolution frequency of the charged particle beam on the design orbit, and generates the variable delay time signal on the basis of said variable delay time.

4. The induction accelerating device according to claim 2 or 3, **characterized in that** said induced voltage arithmetic unit calculates an acceleration voltage value in real time on the basis of the beam deflection magnetic field strength signal indicating the magnetic field strength of the bending magnet that constitutes the synchrotron, and receives the pulse corresponding to the variable delay time from said variable delay time generator to generate the pulse for controlling on/off an induced voltage for acceleration.

5. An acceleration method of a charged particle beam in a synchrotron, **characterized by** comprising the steps of:

controlling generation timing of induced voltages including a positive induced voltage and a negative induced voltage applied from a set of induction accelerating device;
 25 intermittently applying the induced voltages; and thus
 temporally separating functions of a barrier voltage for confinement of a charged particle beam in an advancing axis direction and an induced voltage for acceleration for accelerating the charged particle beam.

6. The induction accelerating device according to any one of claims 1 to 4, **characterized in that** a plurality of said induction accelerating cells are provided according to said functions.

7. The acceleration method of a charged particle beam according to claim 5, **characterized in that** a plurality of said induction accelerating cells are provided according to said functions.

8. An accelerator for accelerating an arbitrary charged particle beam, **characterized by** comprising:

an injection device including an ion source that generates charged particles, a preinjector that accelerates said charged particles up to a certain energy level, and an injector that injects a charged particle beam accelerated by said preinjector into an annular vacuum duct having a design orbit therein;
 40 an induction synchrotron including a bending electromagnet that is provided on a curved portion of said design orbit and ensures the design orbit of said charged particle beam (a bunch), a focusing electromagnet that is provided on a linear portion of said design orbit and ensures strong focusing of said charged particle beam, a bunch monitor that is provided in said vacuum duct and detects passage of the charged particle beam, and an induction accelerating device connected to said vacuum duct for controlling acceleration of the charged particle beam; and
 45 an extraction device including an extractor that extracts the charged particle beam accelerated up to a predetermined energy level by said induction synchrotron to a beam utility line,

wherein said induction accelerating device is an induction accelerating device according to any one of claims 1 to 4 and 6.

9. The accelerator according to claim 8, **characterized in that** said preinjector is an electrostatic accelerator, a linear induction accelerator, or a small-sized cyclotron.

Fig. 1

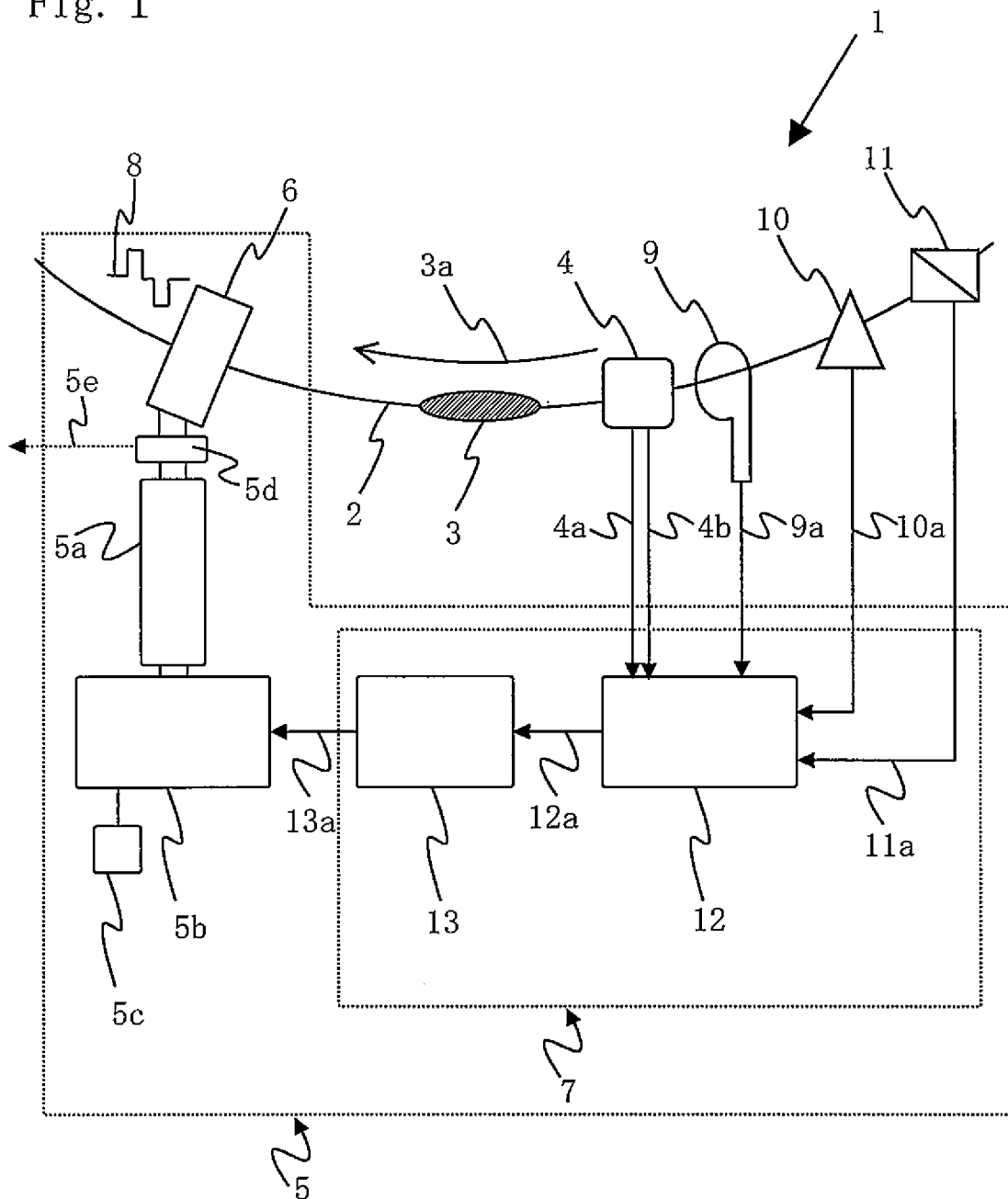


Fig. 2

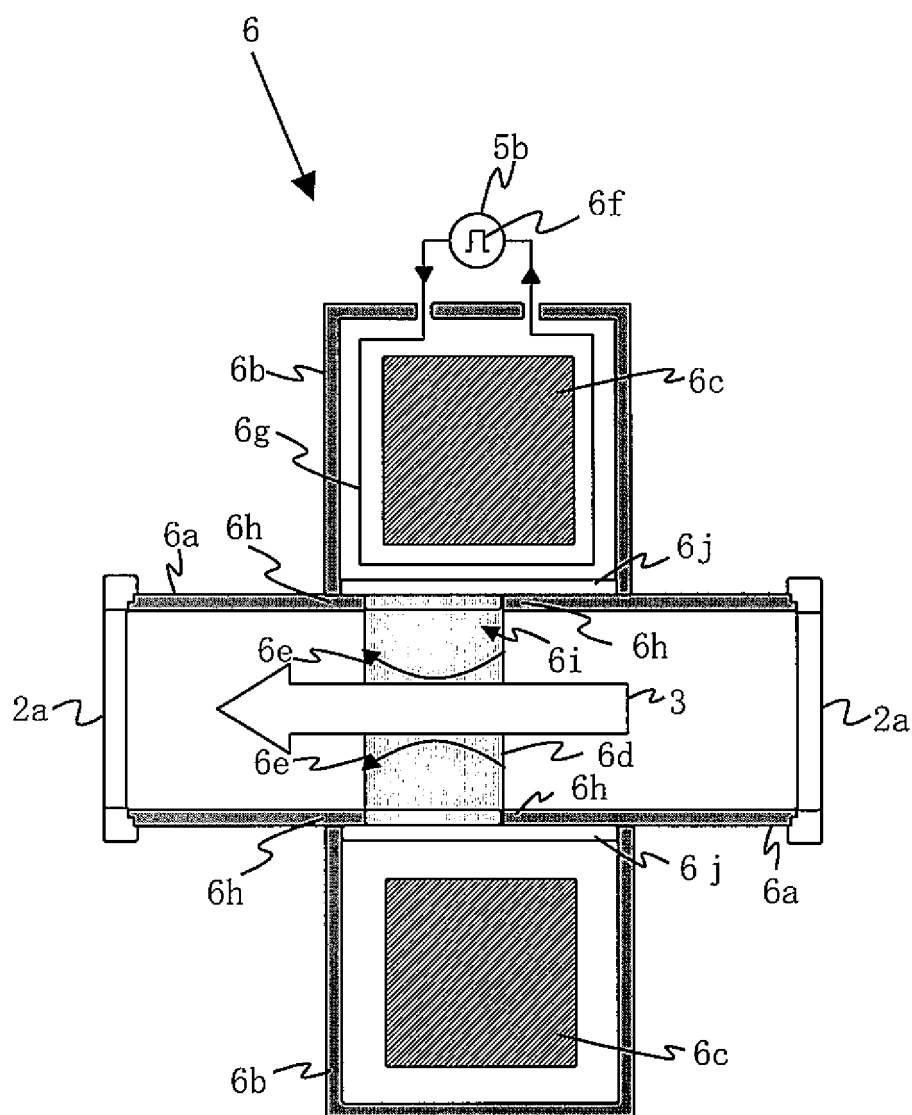


Fig. 3

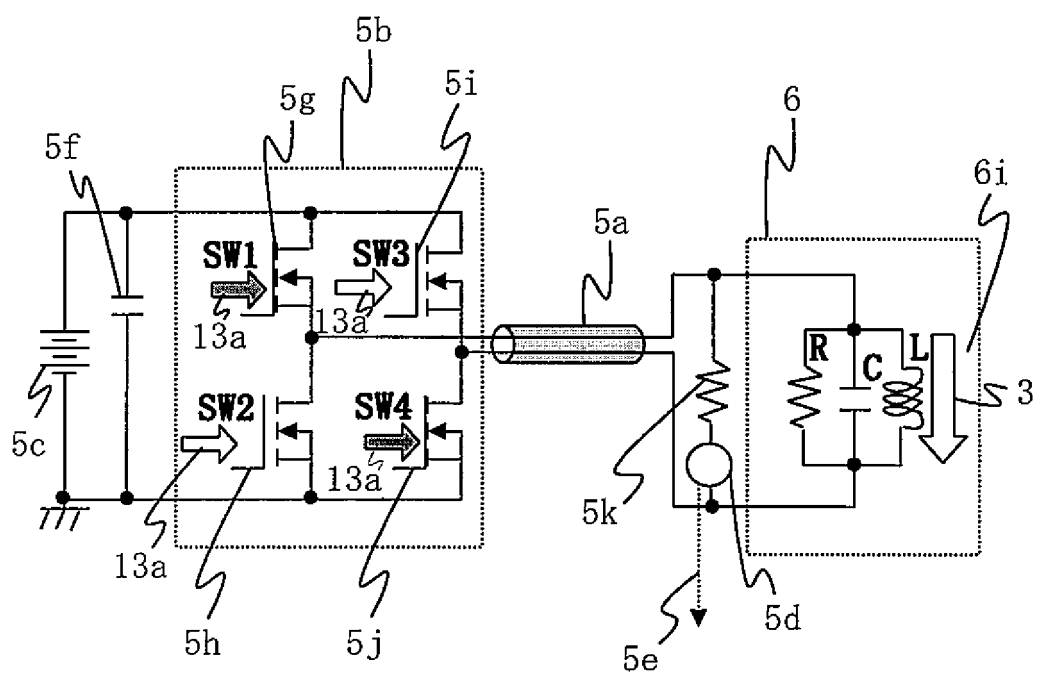


Fig. 4

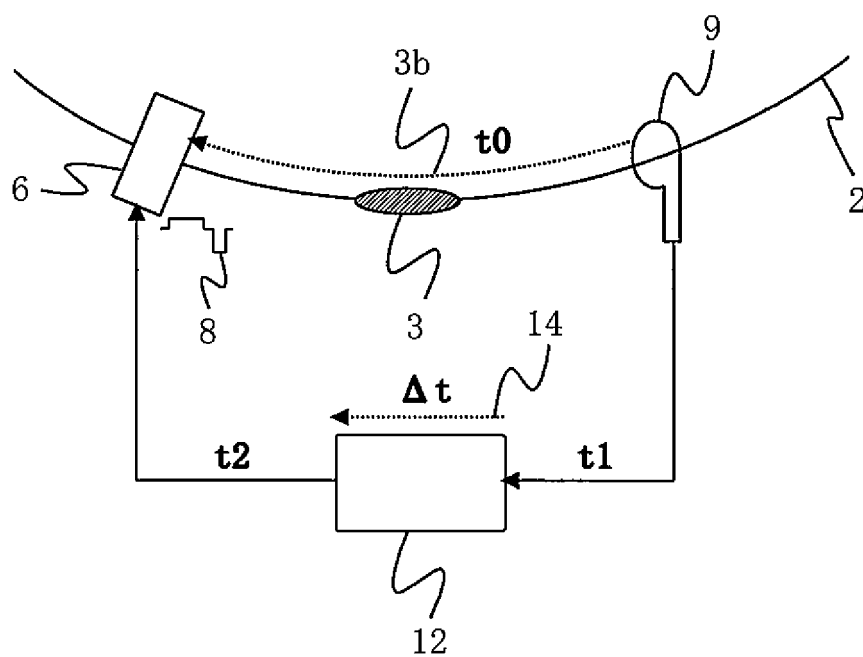


Fig. 5

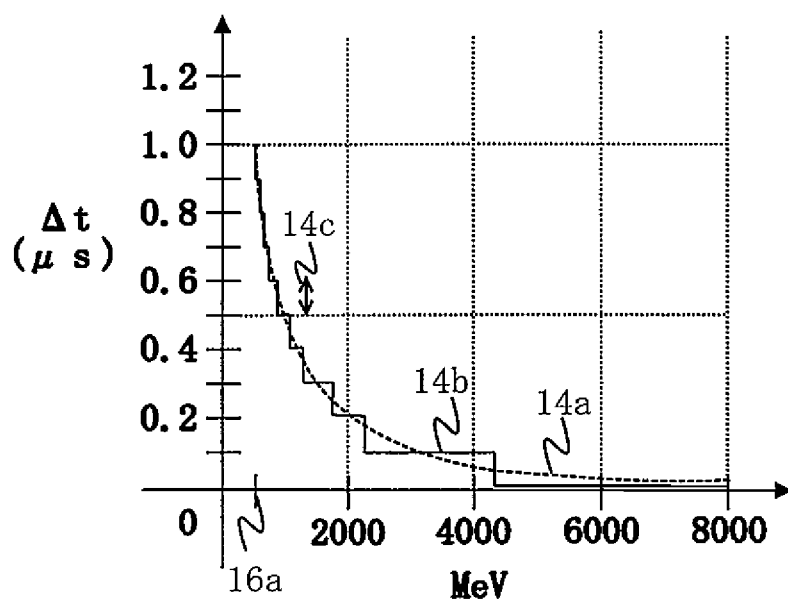


Fig. 6

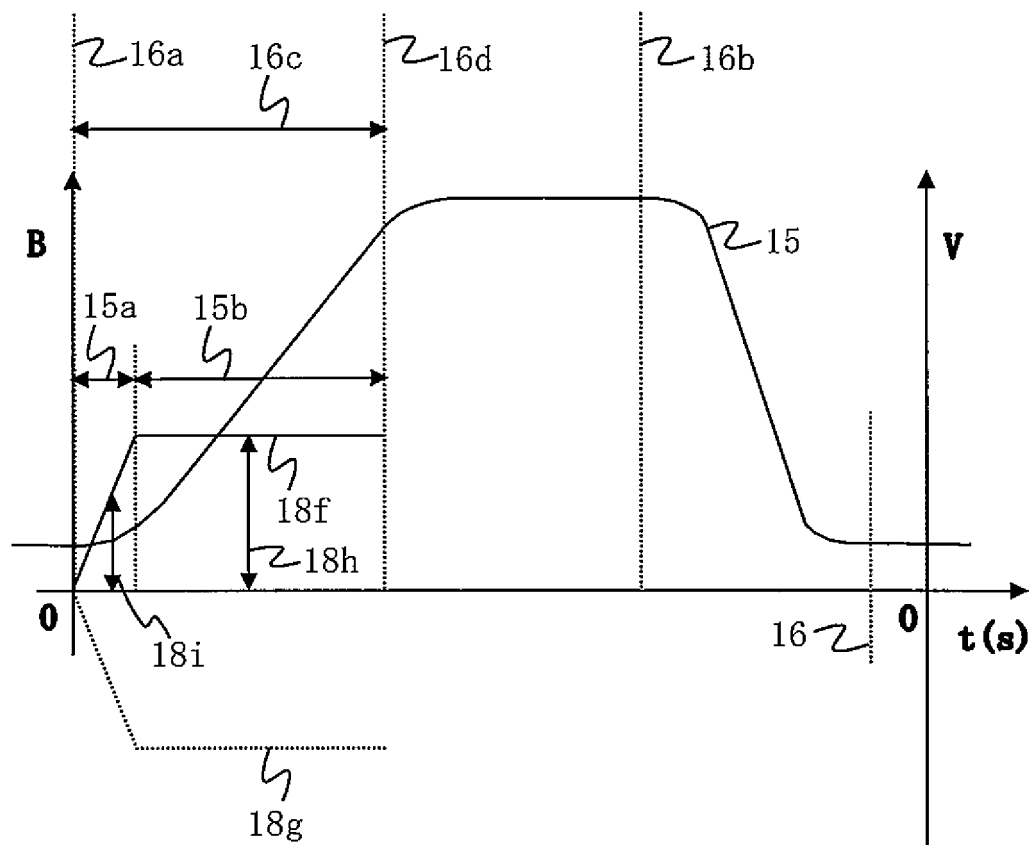


Fig. 7

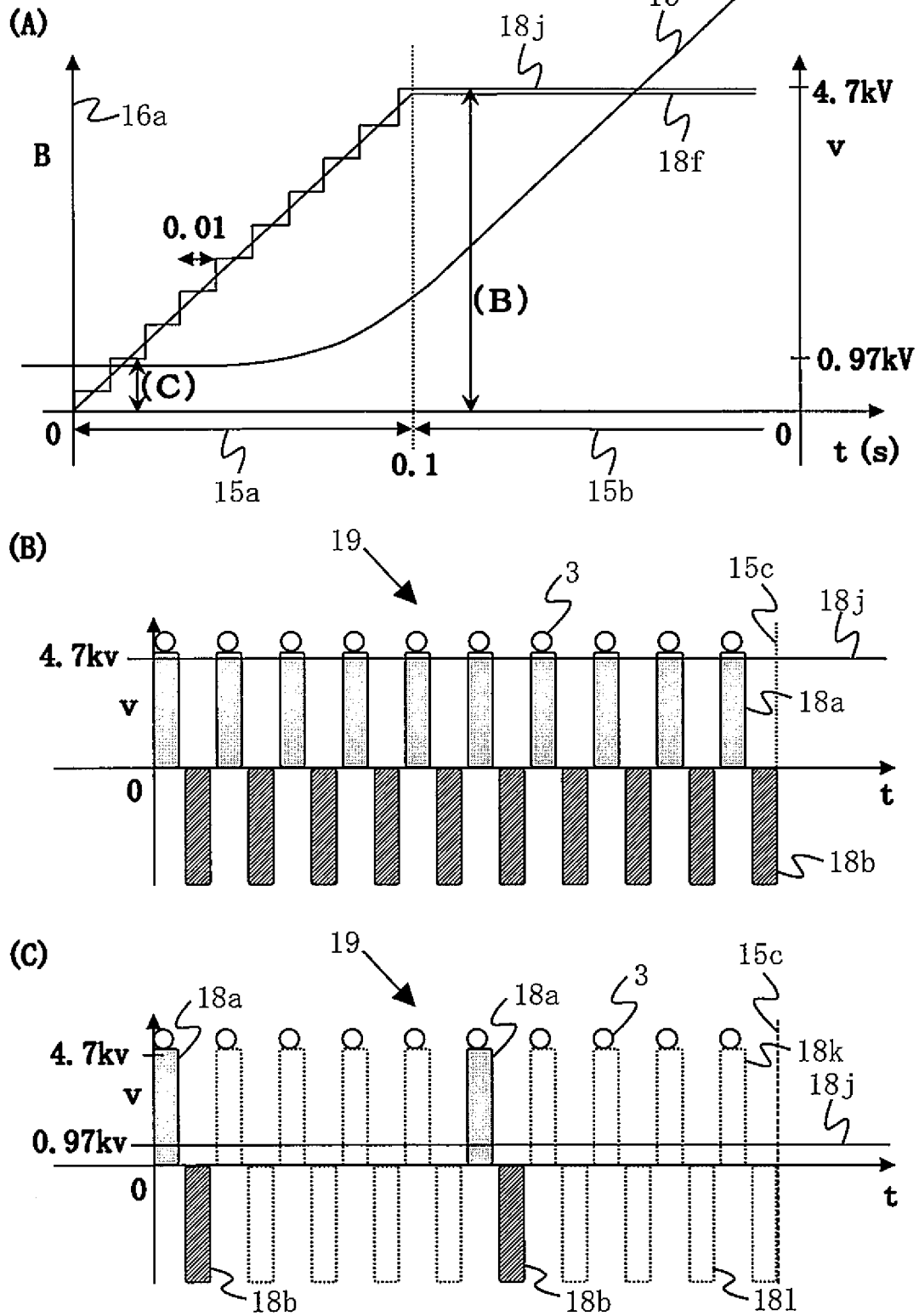


Fig. 8

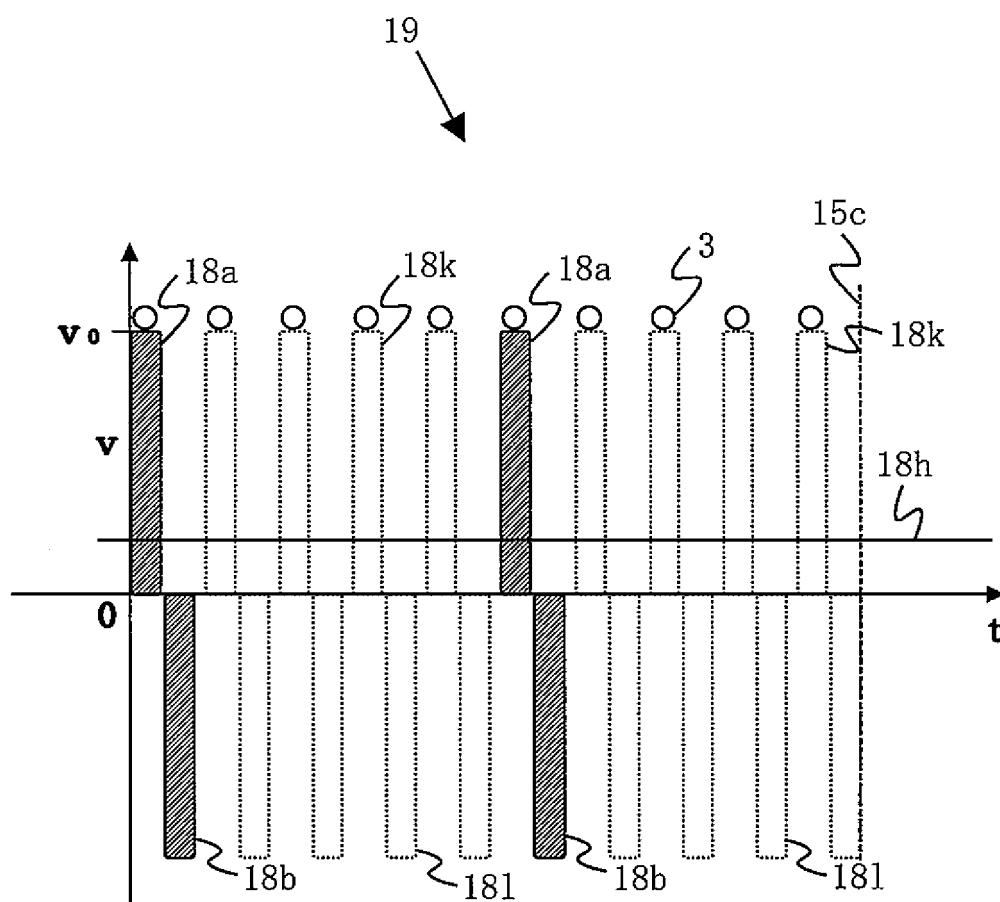


Fig. 9

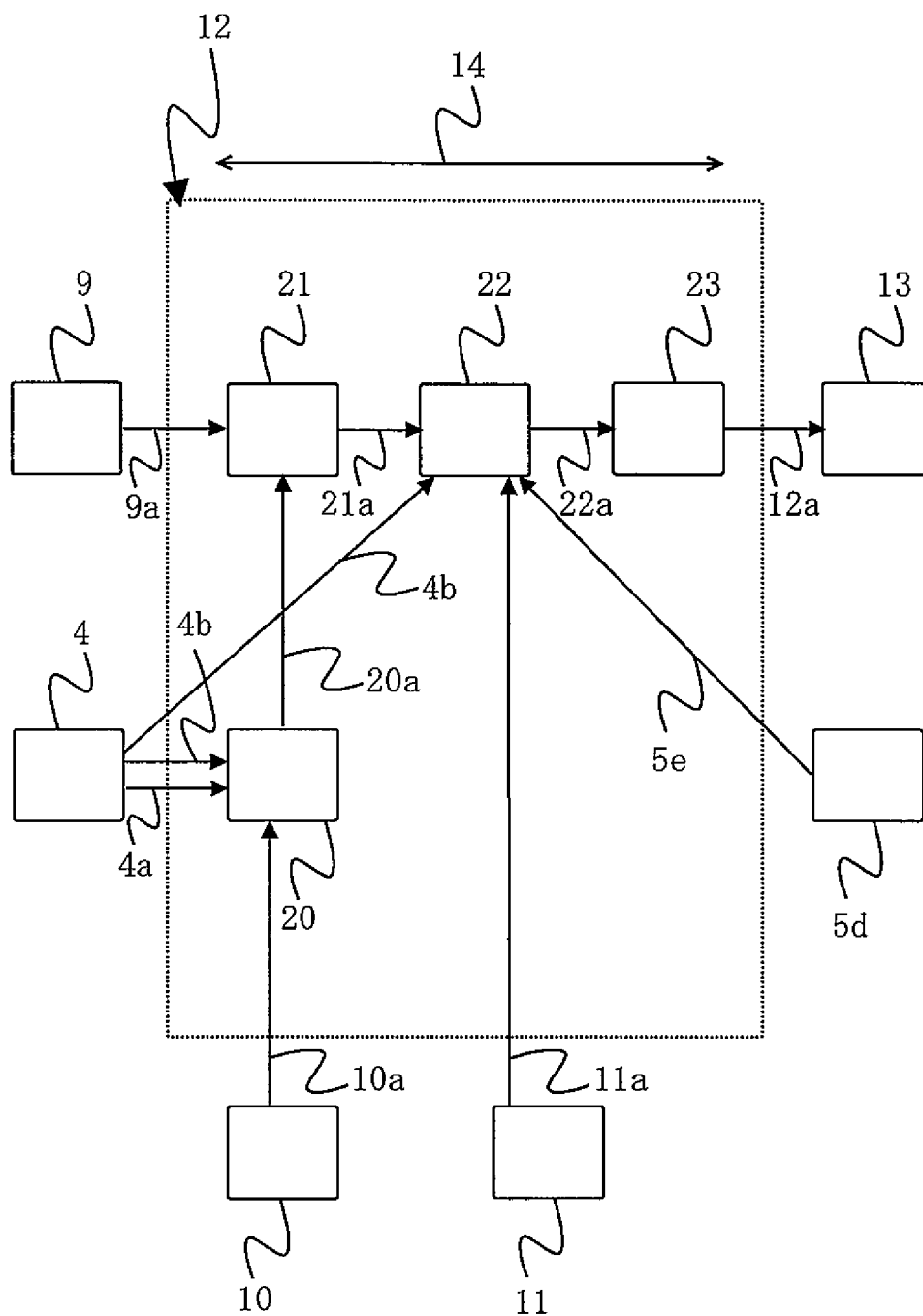


Fig. 10

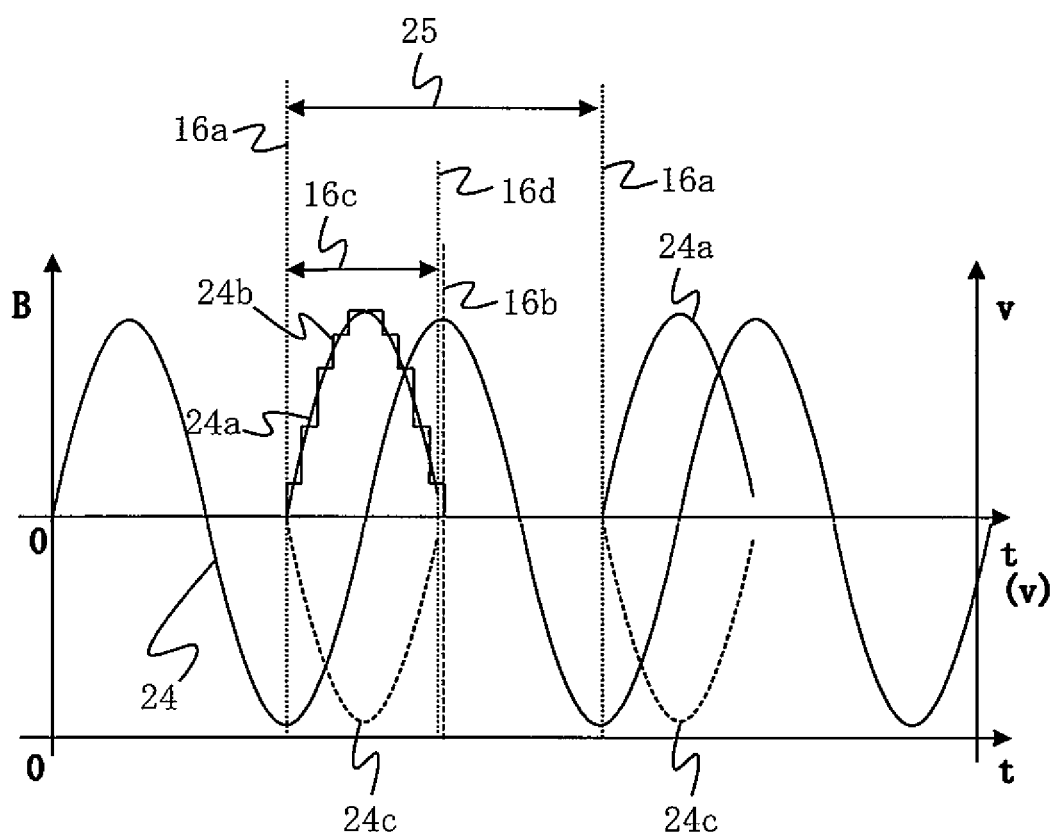


Fig. 1 1

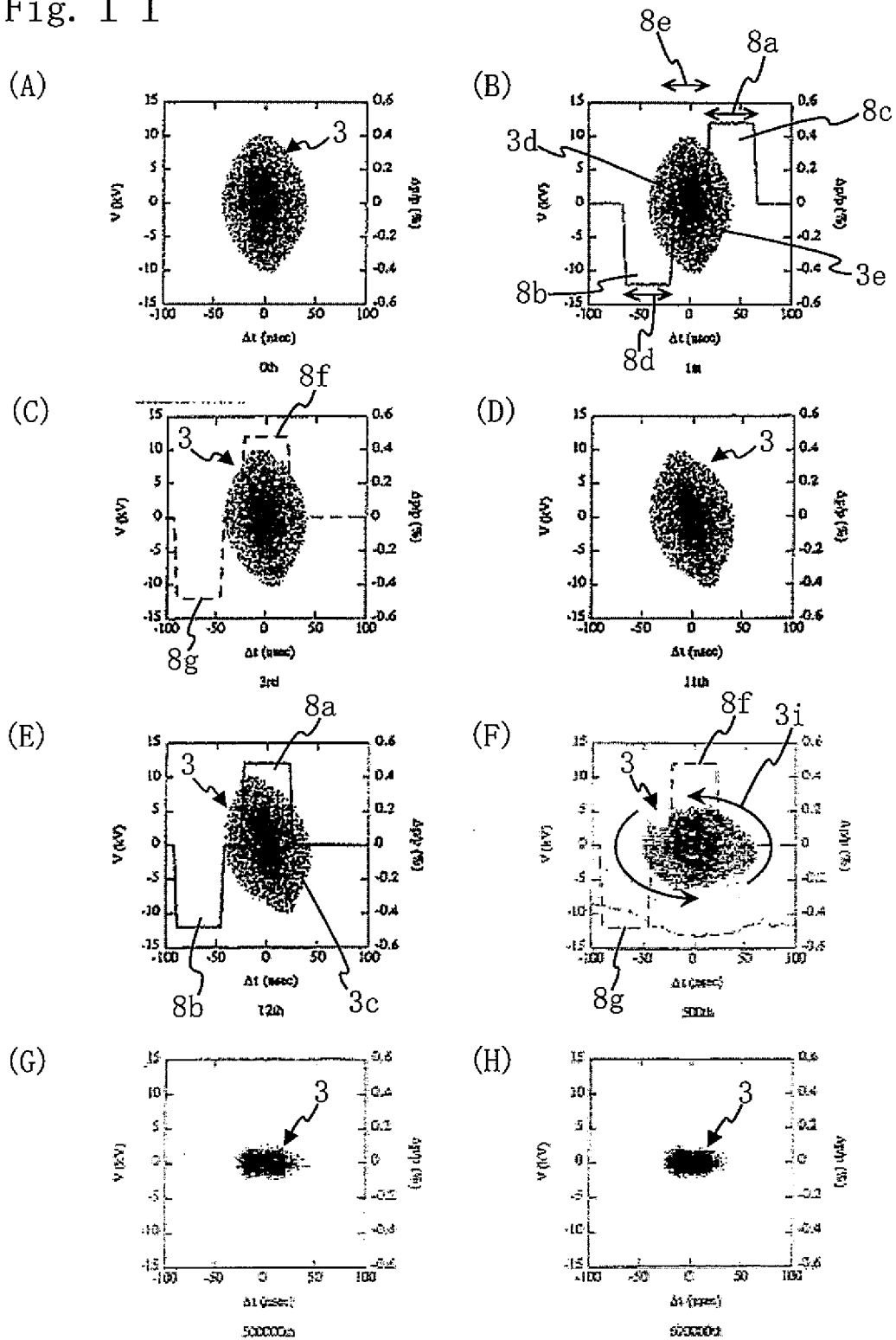


Fig. 1 2

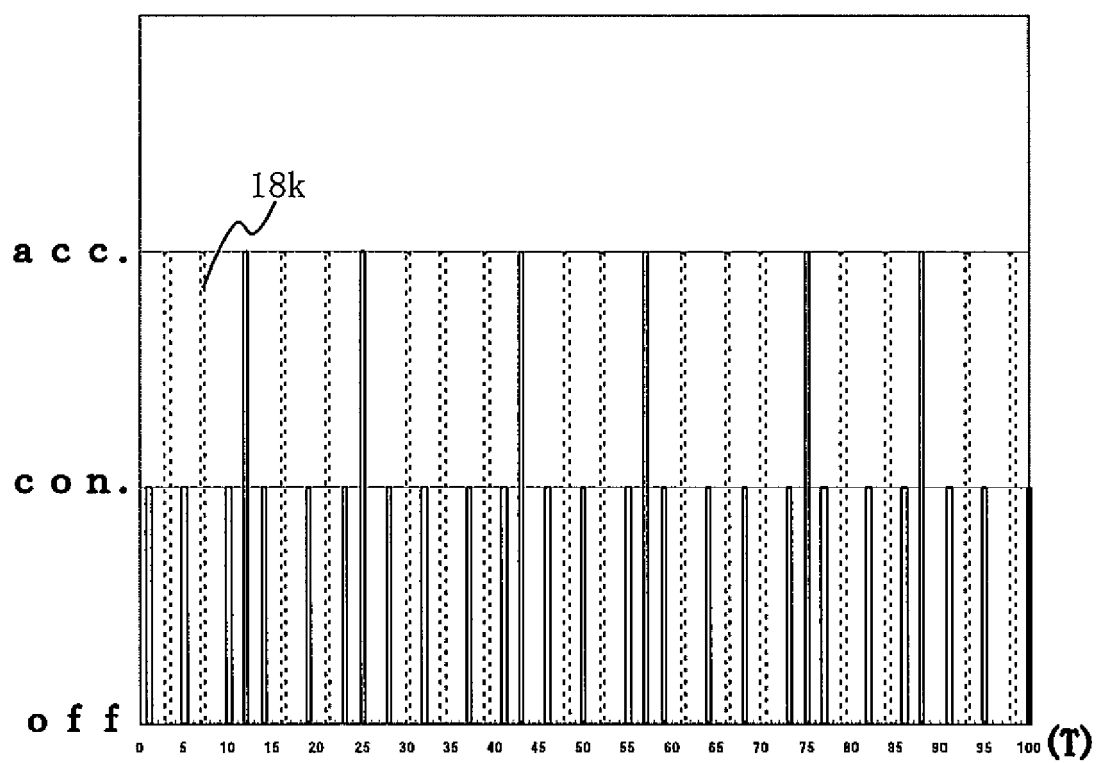


Fig. 13

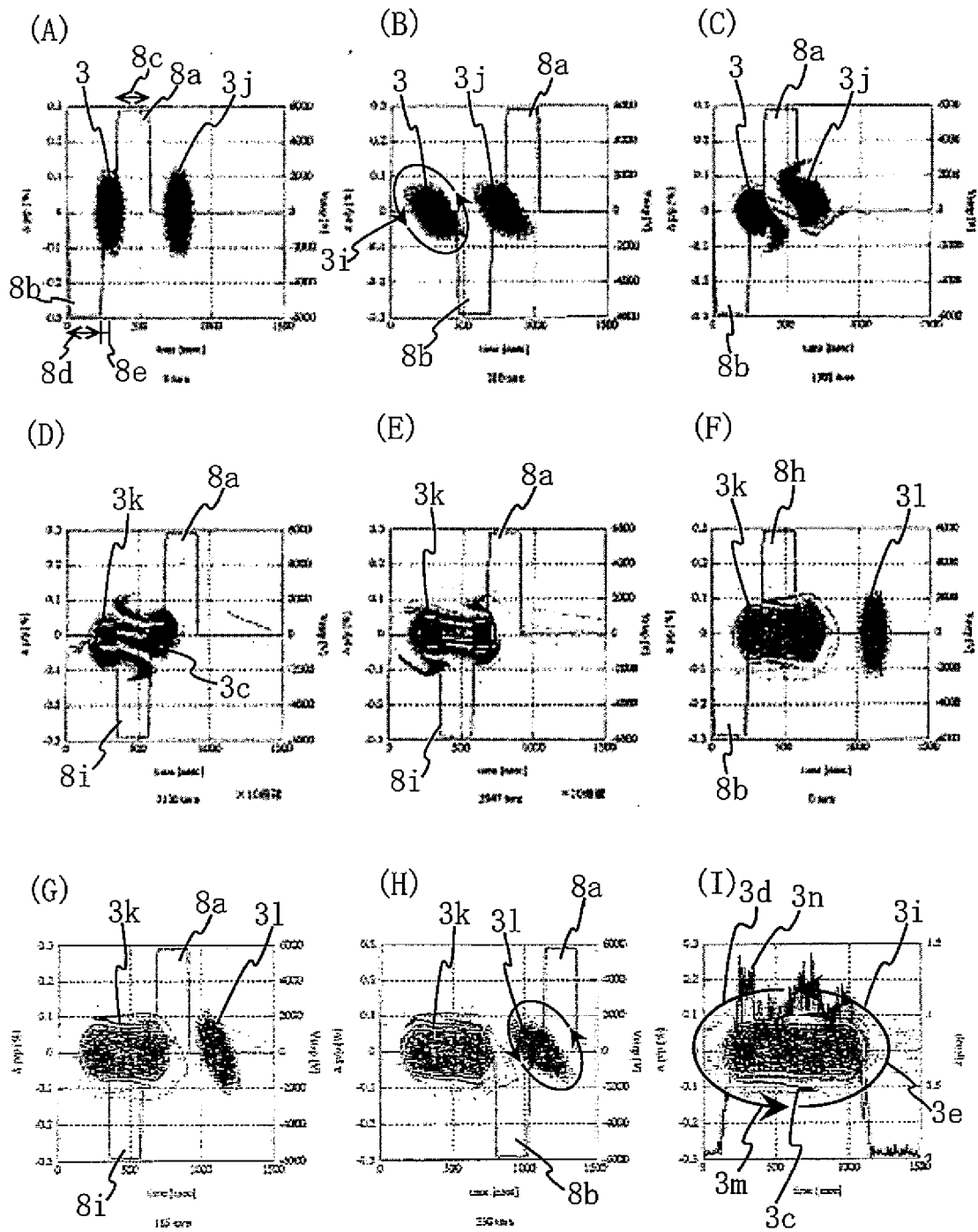


Fig. 1 4

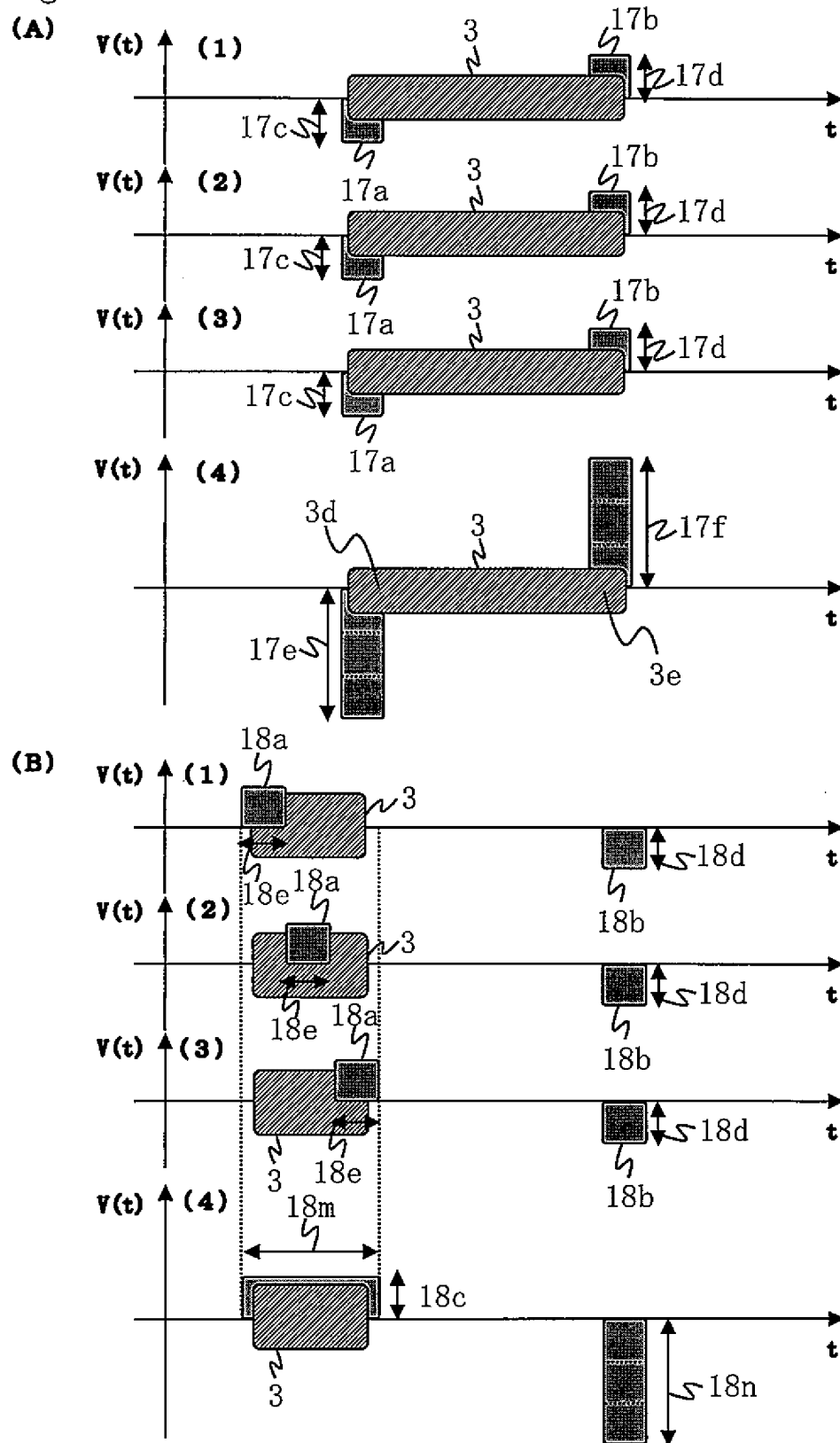


Fig. 15

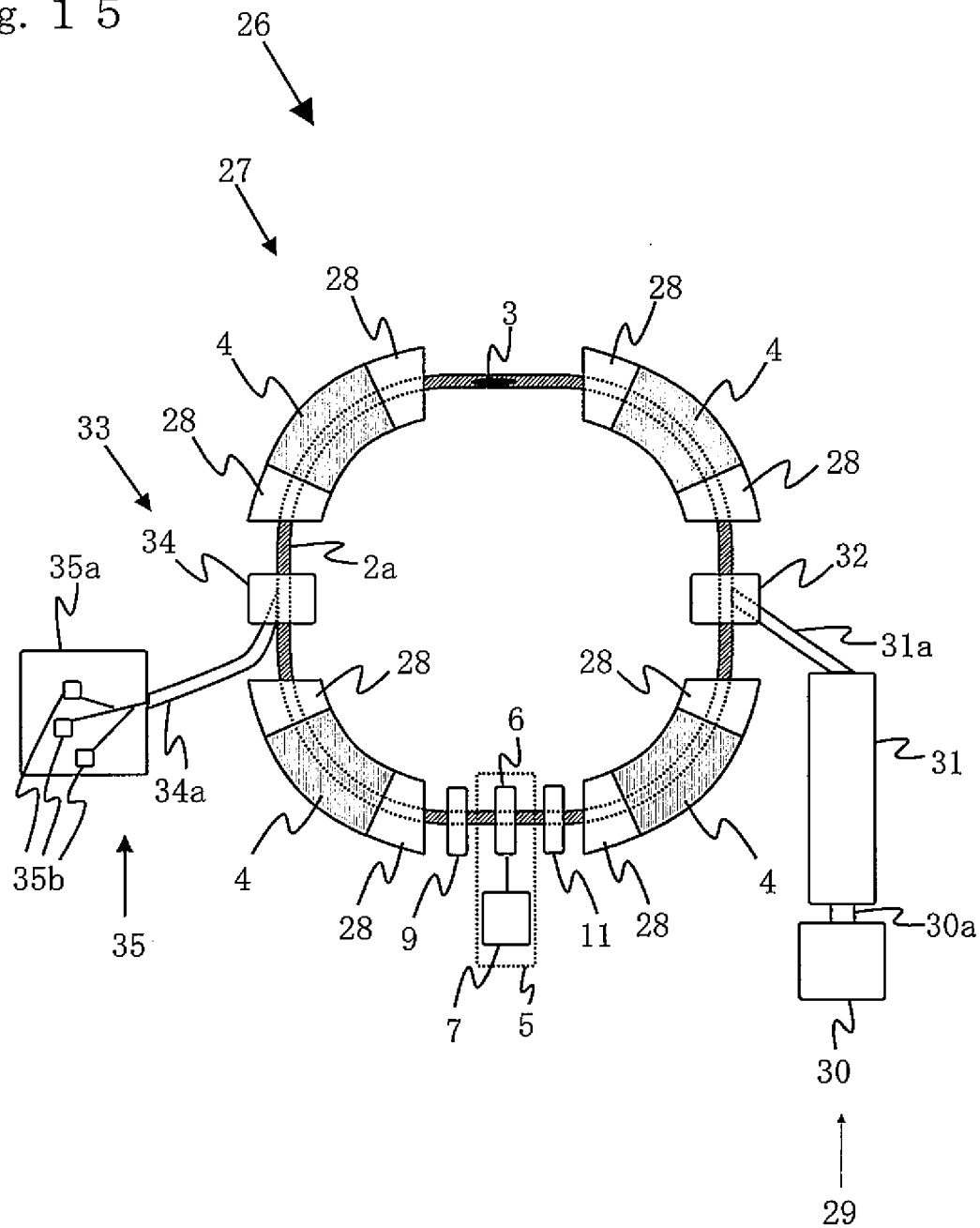
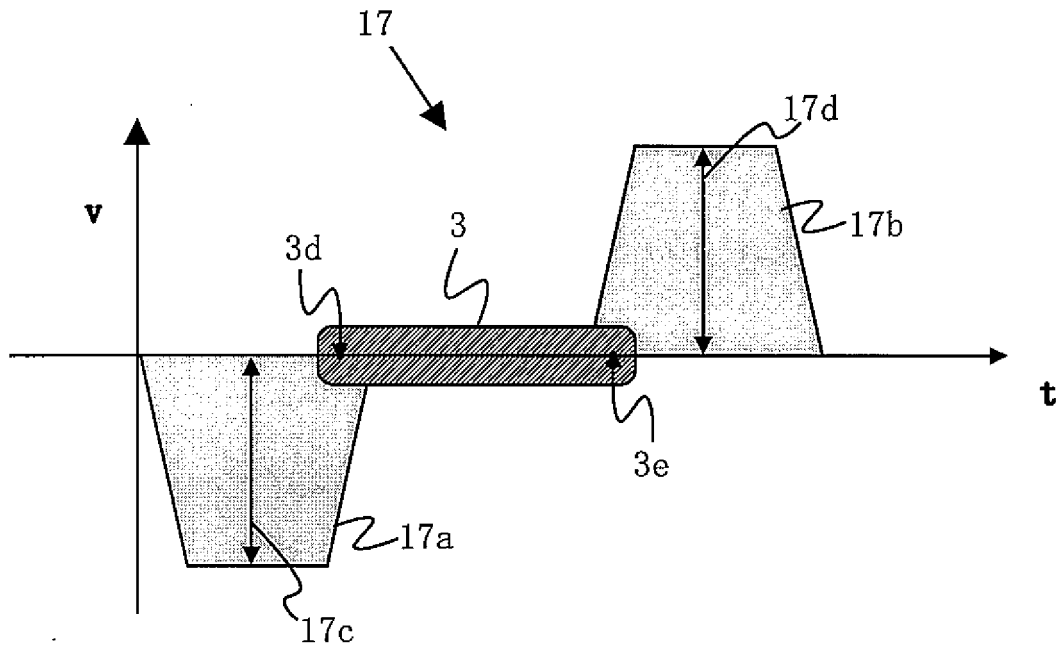


Fig. 1 6
(A)



(B)

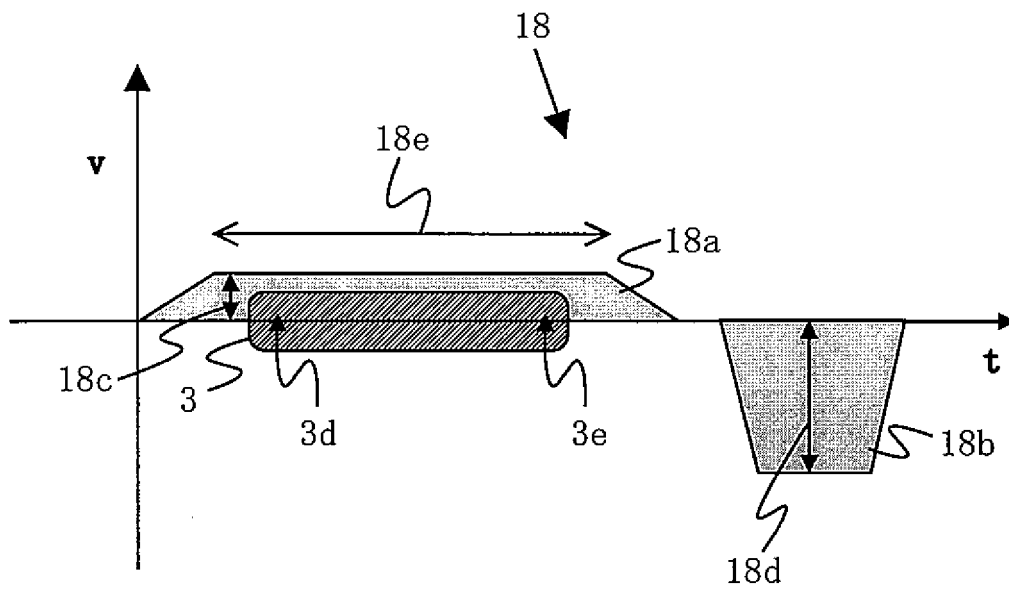


Fig. 1 7

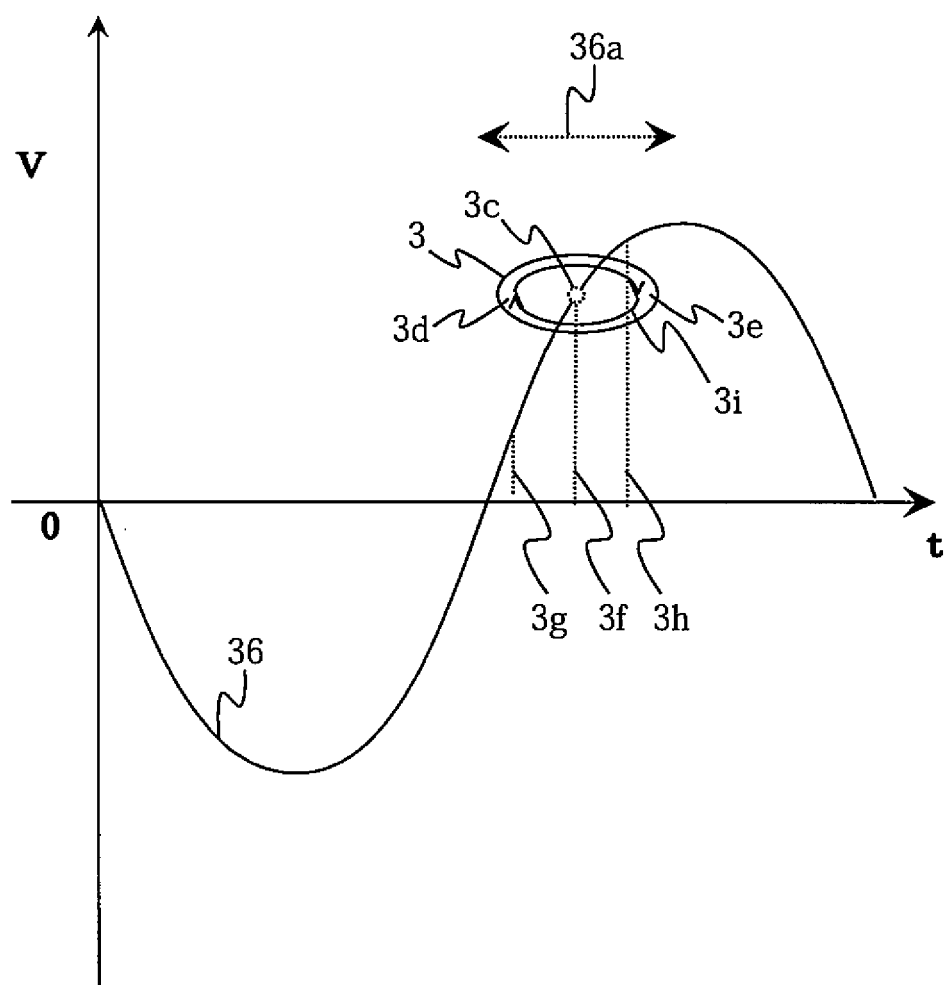
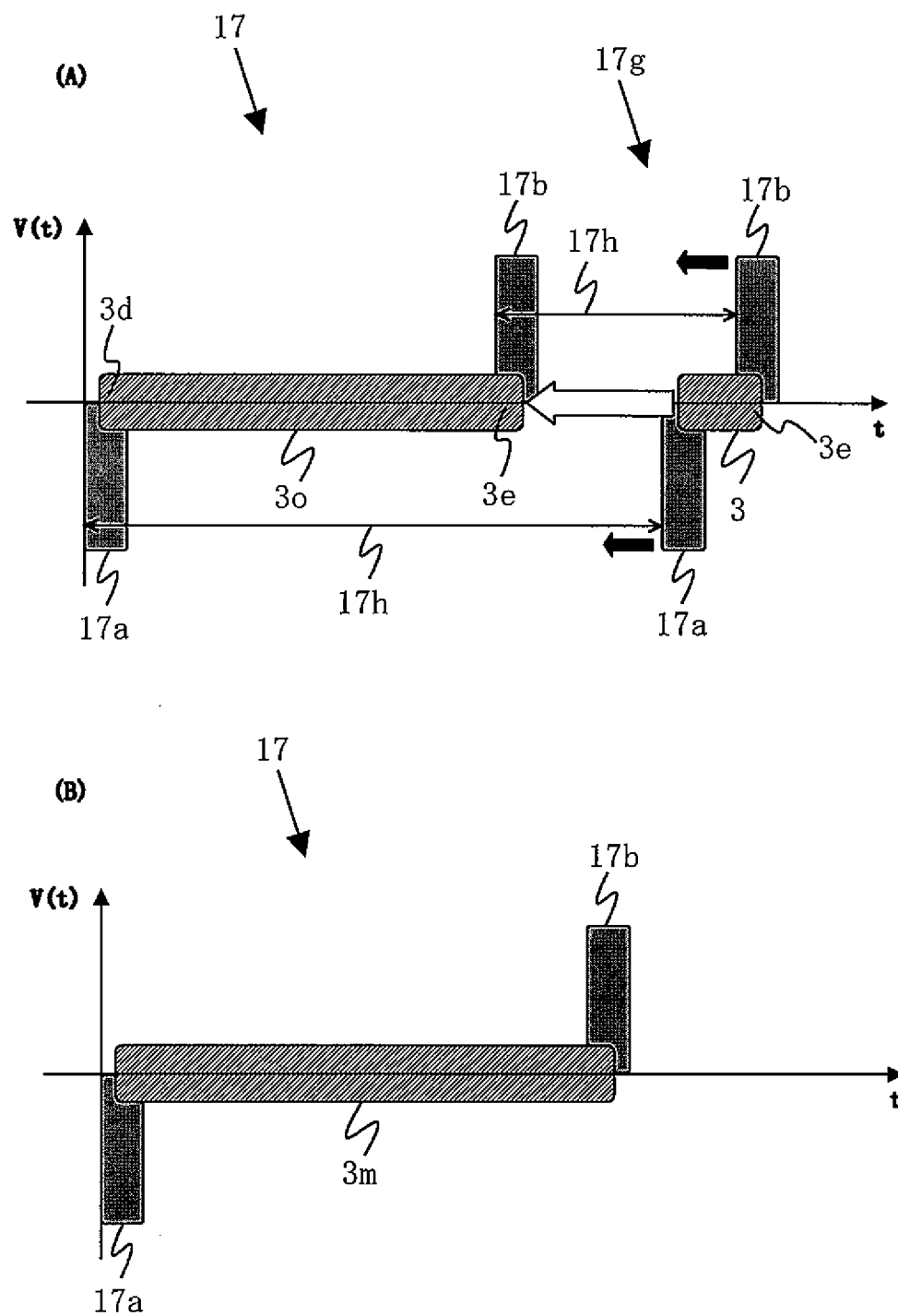


Fig. 1 8



INTERNATIONAL SEARCH REPORT

International application No.

PCT/JP2006/325129

A. CLASSIFICATION OF SUBJECT MATTER

H05H13/04 (2006.01) i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

H05H13/04

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Jitsuyo Shinan Koho	1922-1996	Jitsuyo Shinan Toroku Koho	1996-2007
Kokai Jitsuyo Shinan Koho	1971-2007	Toroku Jitsuyo Shinan Koho	1994-2007

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X Y	Ken Takayama and Super-bunch Group, Progress in Induction Synchrotron R&D: First result of induction acceleration in the KEK Proton Synchrotron, AIP conference Proceedings, US, American Institute of Physice, 08 June, 2005 (08.06.05), vol.773, P281-285	1 2-4, 6, 8, 9
Y	Kota Torikai, Ken Takayama, Superbunch Project Team, First Induction Acceleration of a Proton Bunch In a Circular Ring, 2004 November	2-4, 6, 8, 9

☒ Further documents are listed in the continuation of Box C.
 ☐ See patent family annex.

* Special categories of cited documents:	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A" document defining the general state of the art which is not considered to be of particular relevance	"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"E" earlier application or patent but published on or after the international filing date	"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"&" document member of the same patent family
"O" document referring to an oral disclosure, use, exhibition or other means	
"P" document published prior to the international filing date but later than the priority date claimed	

Date of the actual completion of the international search
14 February, 2007 (14.02.07)Date of mailing of the international search report
27 February, 2007 (27.02.07)Name and mailing address of the ISA/
Japanese Patent Office

Authorized officer

Facsimile No.

Telephone No.

INTERNATIONAL SEARCH REPORT

International application No.

PCT/JP2006/325129

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X Y	Ken Takayama, Kota Torikai, Yoshito Shimosaki, Yoshio Arakida, All-ION Accelerator: A New Turn of The Induction Synchrotron, Proceedings of the 2nd Annual Meeting of Particle Accelerator Society of Japan and the 30th Linear Accelerator Meeting in Japan, JP, Particle Accelerator Society of Japan, 2005 July, P132-135	5-7 4, 6, 8, 9
A	Torikai Kota, Arakida Yoshio, Otsuka Kazunori, Kishiro Junichi, Kono Tadaaki, Nakamura Eiji, Shimosaki Yoshito, Toyama Takeshi, Wake Masayoshi, POP Experiment (I) of Induction Synchrotron: Induction Acceleration of a Single RF Bunch and Formation of a Superbunch in the KEK-PS, Proceedings of the 2nd Annual Meeting of Particle Accelerator Society of Japan and the 30th Linear Accelerator Meeting in Japan, JP, Particle Accelerator Society of Japan, 2005 July, P34-36	1-9
A	Kota Torikai, Yoshio Arakida, Eiji Nakamura, Tadaaki Kono, Yoshito Shimosaki, Takeshi Toyama, Masayoshi Wake, Junichi Koshiro and Ken Takayama, Induction system for a Proton Bunch Acceleration in Synchrotron, Proceedings of 2005 Particle Accelerator Conference, 28 October, 2005 (28.10.05), P1398-1400	1-9
A	Ken Takayama, K.Koseki, K.Torikai, A.Tokuchi, E.Nakamura, Y.Arakida, Y.Shimosaki, M.Wake, T.Kono, D.Arakawa, K.Horioka, S.Igarashi, T.Iwashita, A.Kawasaki, J.Kishiro, M.sakuda, H.Sato, M.Shirakata, T.Sueno, T.Toyama, M.Watanabe and I.Yamane, Induction Acceleration of a Single RF Bunch in the KEK PS, Proceedings of 2005 Particle Accelerator Conference, 28 October, 2005 (28.10.05), P1579-1681	1-9
A	Kota Torikai, Kunio Koseki, Eiji Nakamura, Yoshito Shimosaki, Yoshio Arakida, Tadaaki Kono, Takeshi Toyama, Masayoshi Wake, Ken Takayama, Induction Accelerating Cavity for a Circular Ring Accelerator, Proceedings of EPAC 2004, 24 November, 2004 (24.11.04), P704-706	1-9
E, A	WO 2006-118065 A1 (Inter-University Research Institute Corporation High Energy Accelerator Research Organization), 09 November, 2006 (09.11.06), Full text; all drawings (Family: none)	1-9

Form PCT/ISA/210 (continuation of second sheet) (April 2005)

INTERNATIONAL SEARCH REPORT

International application No.

PCT/JP2006/325129

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
E, A	JP 2007-18849 A (Inter-University Research Institute Corporation High Energy Accelerator Research Organization), 25 January, 2007 (25.01.07), Full text; all drawings (Family: none)	1-9

Form PCT/ISA/210 (continuation of second sheet) (April 2005)

INTERNATIONAL SEARCH REPORT

International application No.

PCT/JP2006/325129

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

Claims 1-4, and 6-8 are directed to an induction accelerator in a synchrotron provided with a predetermined cell, a power source, etc.

Claims 5 and 7 are, however, directed to a method of accelerating an electrically-charged particle beam of a synchrotron to which an induction voltage is intermittently applied.
Therefore, there is no single technical feature between both of them.

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☒ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest
the

- ☐ The additional search fees were accompanied by the applicant's protest and, where applicable, payment of a protest fee..
- ☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- ☐ No protest accompanied the payment of additional search fees.

Form PCT/ISA/210 (continuation of first sheet (2)) (April 2005)

REFERENCES CITED IN THE DESCRIPTION

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Non-patent literature cited in the description

- *Phys. Rev. Lett.*, 2005, vol. 94 (144801-4 [0016]
- *bulletin of the Physical Society of Japan*, 2004, vol. 59 (9), 601, 610 [0017]